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Paludiculture or paludifuture?

Environmental and economic analysis of cattail-based insulation material from paludiculture in The Netherlands

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List of abbreviations

Abbreviation	Meaning
AS	Alternative system/scenario
CH_4	Methane
CO_2	Carbon dioxide
DW	Dry weight
eq	equivalent(s)
EU (ETS	European Union (Emission Trading Scheme)
FAO	Food and Agriculture Organization of the United Nations
f.u.	Functional unit
GHG(s)	Greenhouse gas(ses)
GWP	Global Warming Potential
ha	Hectare
HDPE	High-density polyethylene
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organisation for Standardisation
LCA	Life-cycle Assessment
LCI	Life-cycle Inventory
LCIA	Life-cycle Impact Assessment
LULUCF sector	Land use, land use change and forestry sector
Mt	Megatons
N_2O	Nitrous oxide
NPV	Net present value
OM	Organic matter
PAS2050	Publicly Available Specification 2050
R	Thermal resistance
RS	Reference system/scenario
t	Ton
yr	Year

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Abstract

Dutch peatlands have a long drainage history to facilitate agriculture, leading to relatively high greenhouse gasses (GHGs). Paludiculture, defined as cultivation on wet and rewetted peatlands, is often seen as a viable climate warming mitigation option to reduce GHGs and counteract land subsidence of peatlands, while at the same time providing a profitable agricultural business. The *paludicrop* cattail can be used for e.g. insulation material. There is a growing demand for eco-friendly thermal insulators as cattail, which are needed to equilibrate the trade-off between the reduction in energy demand for heating along with insulation materials and their related environmental impact.

The aim of this research is to give insight in the optimisation of 1 hectare agricultural Dutch peatland, from a climate and economic perspective. Two combined systems are compared, with the peatland provisioning either dairy or insulation material. This is done by performing a consequential one-factor *lifecycle assessment* (GHGs) and a cost-benefit analysis combined with carbon credits. The reference system implies dairy farming with drainage on peatlands and fossil-based insulation material (glass/stone wool). The alternative system implies dairy farming replaced to set-aside West-European land and cattail insulation produced from paludiculture on the peatlands. Biogenic carbon storage is excluded (ISO-standards) and included (PAS2050-methodology).

It can be concluded that, from a climate's perspective, the switch towards cattail-focussed paludiculture is accompanied with a high GWP-reduction potential. In an optimal scenario, the system change could result in an almost positive GWP balance (incl. biogenic storage) compared to the current situation. The negative contributions in the Global Warming Potential (GWP) can be mainly attributed to the avoided GHG emissions from draining peatlands, followed by the biogenic C-storage in the cattail plates. Cattail-focussed paludiculture is not (yet) competitive with dairy farming, however, a relatively low carbon commodity price can result in an interesting business case and comparable income for paludiculture compared to dairy farming.

Cattail-focussed paludiculture has a high potential to reduce GHGs from peatlands and to achieve negative emissions, i.e. to actively reduce the CO_{2}.-eq-concentration in the atmosphere, while at the same time building on the biobased economy. Further research should focus on gathering more empirical data, stakeholder analysis and optimising the business case (for producers/consumer).

Keywords: peatland restoration, paludiculture, carbon mitigation, bio-based insulation, cattail, peatland economics

Executive summary

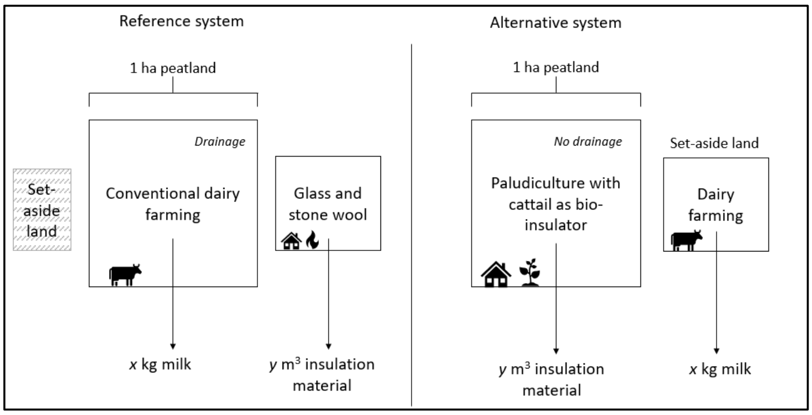
Dutch peatlands are responsible for more than half of the amount of greenhouse gasses (GHGs) from agriculture, whereas they only cover less than 10% of Dutch agricultural area. Reducing the emissions, currently accounting for an estimated 3-5% (7 Megatons (Mt) CO_2) of Dutch total GHG-emissions, is needed. One of the goals described in the Dutch Climate Agreement is to reduce the emissions from Dutch peatlands with 1 Mt CO_2eq by 2030. Paludiculture, defined as cultivation on wet and rewetted peatlands, is often seen as a viable climate warming mitigation option to reduce GHGs and counteract land subsidence of peatlands, while at the same time providing a profitable agricultural business. Cattail is a *paludicrop* and is known for its good insulation properties. Therefore, switching to cattail-focussed paludiculture might be a solution to reduce GHGs from peatland with continued land use, while providing a profitable business and building on the bio-based economy. Currently, there is a trade-off between the reduction in energy demand for heating along with insulation materials and their related environmental impact. This results in a growing demand for eco-friendly thermal insulators as cattail, being a sustainable alternative for current insulators such as polyurethane or mineral wool.

The aim of this research is to provide insights into the optimisation of 1 hectare (ha) peatland focussing on land use, from a climate and economic perspective.

Methodology

Consequential one-factor Life cycle assessment (GHGs)

A life cycle assessment (LCA) is performed to give insights in the in- and outflows of two systems. The compared systems are shown in Key Figure 1.



Key Figure 1: Schematic representation of the reference system (dairy farming) and alternative system (paludiculture).

The peatland provides either milk (*x* kg of Fat and Protein Corrected Milk (FPCM) or insulation material (*y* m^3, or *z* kg with a thermal resistance R of 1 m^2 K/W). This combined gives the functional unit (f.u.): a combination of *x* and *y.* Three elements are investigated: (1) the substitution of fossil-based glass/stone wool in equal share by cattail insulation, (2) the replacement of milk production to set-aside land and (3) rewetting the peatlands from three main drainage categories towards a paludiculture water level (0 to + 20 cm). The total CO_2.eq, expressed in Global Warming Potentials (timespan: 100) in the reference (dairy production) and alternative (cattail insulation) systems are analysed by performing life cycle assessments of milk and insulation material. System boundaries are *cradle-to-farm* for dairy farming, and *cradle-to-gate* for the production of insulation material, assuming a landfilling scenario as end-of-life. Biogenic storage in cattail plates is both excluded (ISO-standard) and included following the PAS2050-methodology. A model is proposed to determine average CO_{2}.eq emissions related to (elevation of the) water level in the two systems.

Cost-benefit analysis

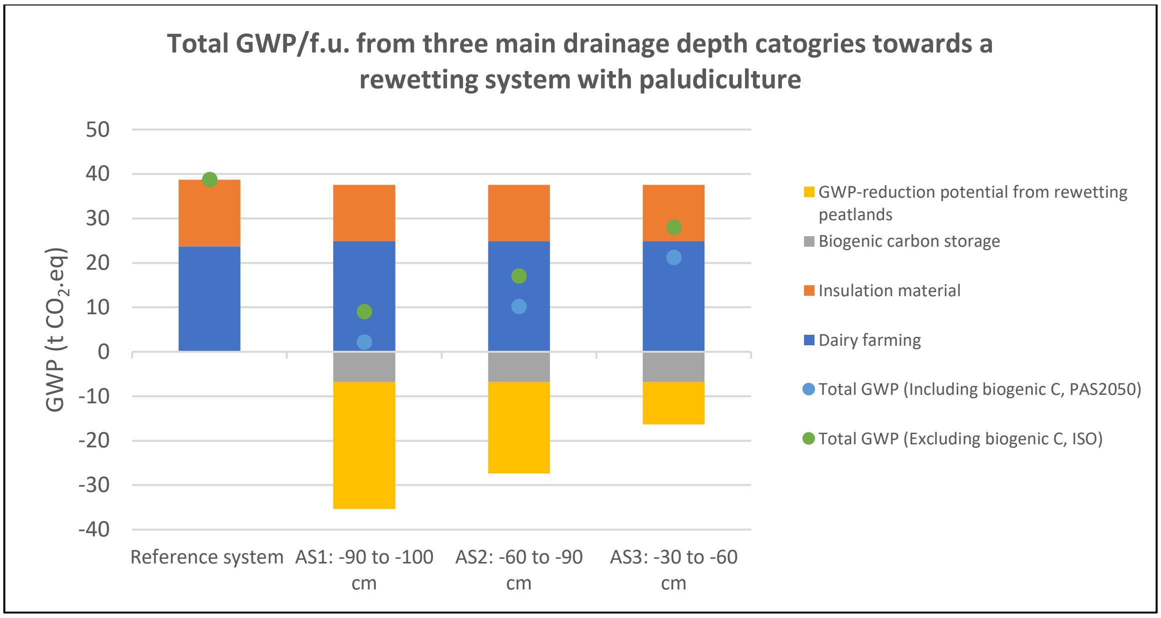
A cost-benefit analysis is performed with the economic viability assessed by calculating the Net Present Value (NPV) and comparing average net yearly income of paludiculture with dairy farming. The assumed discount rate is 6% and project lifetime is 30 years. Costs and benefits are obtained from previous pilot projects and developed economic models. Next to reference economic scenarios, an alternative scenario is proposed for North-Netherlands, i.e. -60 to -90 cm current drainage, valuing GHG emissions with carbon credits by various prices. The yearly carbon break-even price as well as the breakeven price for the NPV is calculated through trial-and-error.

Results

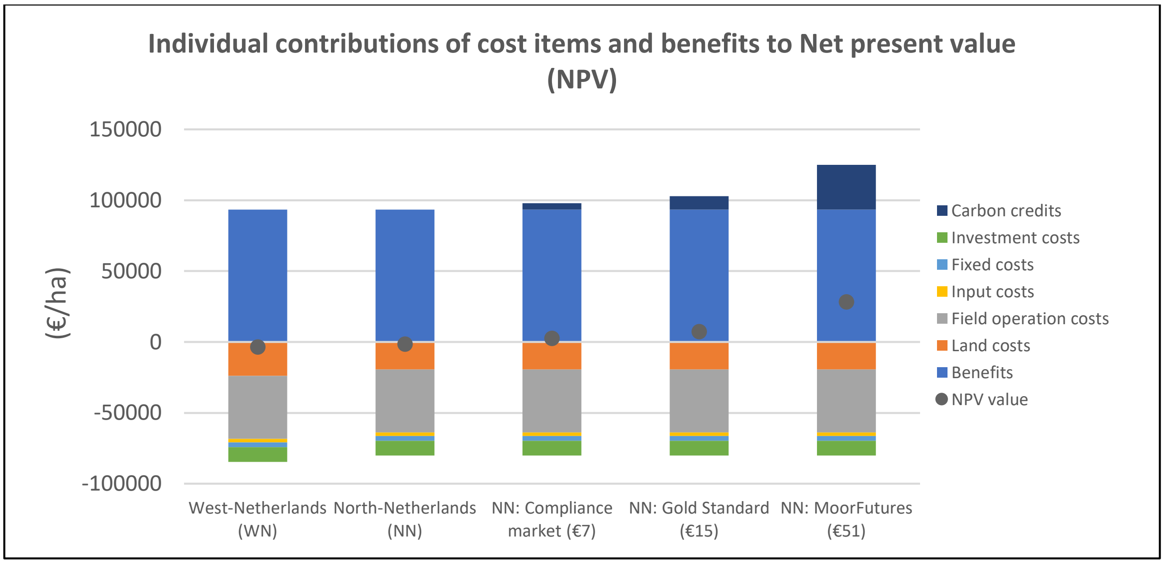
Life cycle assessment

Following a system change from dairy farming with current drainage to a water level associated with cattail-based paludiculture results in a decrease in GWP/f.u. in all alternative systems. A minimum reduction of 27% can be achieved from switching from dairy farming with relatively low drainage towards paludiculture. This can increase with a system change reduction up to 76% from dairy farming with deep drainage towards paludiculture, both percentages excluding biogenic storage. Taken into account the biogenic storage results in a greater reduction of GWP/f.u., with approximately 7 t CO_2.eq stored in the cattail insulation plates. Changing the land use on current deeply drained peatlands (-90 to -100 cm below groundwater level) could result in achieving almost negative emissions.

The negative contributions in the alternative GWP/f.u. can be mainly attributed to the avoided GHG emissions from peatlands. This relative benefit of avoided GHG emissions from rewetting peatlands decreases with a system change coming from a current relatively low drainage depth (-30 to -60 cm below groundwater level). This relative benefit of rewetting peatlands in areas with relatively low drainage depth is almost equal to the benefits of the biogenic carbon storage.



Key Figure 2: Total GWP/f.u. in reference system and in three proposed alternative systems with paludiculture.



Key Figure 3: Individual contributions of cost items and benefits to Net present value (NPV) (project lifetime of 30 years, discount rate 6%), in- and excluding carbon credits.

Economic analysis
It may be concluded (Key Figure 3) that the current NPV for paludiculture is slightly negative, which indicates that it is not yet viable to invest in paludiculture. This can be mainly attributed to high investment costs, relating to landscape design with paludiculture, and high field operation costs, relating to specialised machinery needed for harvesting at wetter soils. The lower land rent price in North-Netherlands results in a higher viability for this region compared to western areas. Moreover, the average net income confirms that cattail-focussed paludiculture is not yet competitive with dairy farming, The average net income from paludiculture for North-Netherlands is roughly €950 ha^{-1}, excluding initial investment costs, and up to €1600 ha^{-1} for dairy farming.

Valuing the avoided carbon emissions with a carbon credit system leads to extra revenues for the farmer, and this research shows that all calculated NPVs are positive when the revenues from carbon credits (varying by price) are added in the default scenario. A yearly carbon commodity price **between the €39 and €40 per ton avoided CO_2-emissions** is needed for average net income to compete with dairy farming. It is revealed that a carbon breakeven price as low as of **€2.64 per t avoided CO_2.eq for a project period of 30 years** is sufficient to obtain a positive NPV-value.

Discussion

The analysis shows that a system change is accompanied with a (high) GWP-reduction potential. Nevertheless, some limitations and suggestions for further research should be given. The research is an exploratory research and is based on several assumptions in both the LCA and economic analysis. As shown by the sensitivity analysis, choosing different assumptions in key parameters could significantly alter results. These mainly include the choice of the reference insulation material, the end-of-life or the assumed yield of milk (for the LCA) and fluctuating benefits and the assumed discount rate (for the economic analysis). Therefore, further research should specifically focus on gathering empirical data to reduce uncertainties about these assumptions. This further research should be accompanied with a higher level of analysis, as the current research is only focussed on a relatively small scale.

Moreover, a focus should be set on the set-aside land in Europe and the displacement of milk production to these areas. It is assumed that these areas are widely available and do not have a GHG emission now, which might be a large simplification of reality. Next to this, the economic analysis is performed from a farmer's view and focusses on one product only, namely cattail insulation. The revenues from carbon credits are fully assigned to the farmer and integrating carbon credits for the biogenic storage or dividing the additional revenues from rewetting the peatlands with producers or consumers might encourage these actors. Cooperation between the chain parties is of great importance in supply chain management. This involves stakeholder analysis from a farmers' as well as producer/consumer perspective, which is not performed for this research but needed for the success of implementing paludiculture in the future. In addition, including high-quality end-use of cattail for construction plates or even the use of cattail in the pharmaceutical nutraceutical could result in a more diverse, and therefore better business case.

Lastly, the water costs for current drainage or water elevation are excluded, but it is expected that if the current policy continues, the burdens of drainage management will rise further because of continuing peat subsidence. Further interesting research could focus on potential avoided costs of implementing paludiculture compared to the current costs for drainage, which might also be relevant for regional water authorities.

Conclusion

This research has provided insights in current land-use related GHGs from milk production and provided insights in the potential GHG-reduction potential of cattail-focussed paludiculture. It can be concluded that paludiculture holds a high potential to reduce GHGs from peatlands and to achieve negative emissions, while at the same time building on the biobased economy. Improving of the business case is identified as a key development for the success of implementing paludiculture and carbon credits could play a role in increasing the economic viability of paludiculture. There should be said that these statements are accompanied by several uncertainties, which are mainly related to assumptions due to a lack of empirical data. This is one of the focus points for further research, next to stakeholder analysis and optimising the business case.

1. Introduction

In recent years, the demand and need for energy services to meet basic human needs and to serve productive processes is increasing (Van der Hilst, 2012). However, the increasing amount of carbon dioxide (CO_2) and other greenhouse gasses (GHGs) caused by fossil fuel industries and other mankind's activities enabling these energy services, is resulting in a rising mean temperature (Mahlman, 1997). The Paris Agreement obligates countries to take climate change and the agreement aims to keep the global temperature rise well below 2.0 degrees Celsius above pre-industrial levels (Hoegh-Guldberg et al., 2018). However, the Intergovernmental Panel on Climate Change (IPCC) stated that human activities have already caused a current increase of 1.0 degrees Celsius (Hoegh-Guldberg et al., 2018). Another concerning trend is that it is likely that the 1.5 degrees Celsius temperature increase is reached between 2030 and 2052 with current trends (Hoegh-Guldberg et al., 2018).

It is known that the rising temperatures can have devastating effects on the human life and ecosystems on Earth, with effects as sea level rise, biodiversity loss, heat extremes, heavy precipitation episodes, droughts as well as a decreased food security (e.g. Kareiva, Kingsolver & Huey, 1993; Parry, Rosenzweig & Livermore, 2005; Trenberth et al., 2014). Given this context and likely climate changes, it can be concluded that actions are needed to reduce human-caused emissions of GHGs (Mahlman, 1997).

Energy consumption in buildings and space heating also contributes to a rise in GHG emissions, with the needed energy for heat derived from non-fossil resources (IEA, 2018). In 2017, households account for 27.2% of final energy consumption in the European Union (EU), which is mainly covered by natural gas (36%) (Eurostat, 2019). Space heating is the main use of energy households, with an estimate of 64.1%. The same can be observed in The Netherlands: The total energy consumption was 3100 petajoules (PJ) in 2018, of which 790 PJ of energy are used for space heating in both utility buildings and households, which is primarily obtained from fossil-based natural gas (93%).

In this context, a rapid and significant reduction in the demand of energy for space heating is crucial to facilitate the transition away from fossil fuels, while achieving sustainable development goals in a synergistic way (De Cian, Pavanello, Randazzo, Mistry & Davide, 2019). Electrification of the energy demand combined with increased renewable energy capacity is often seen as a solution for reducing space demand from fossil-based sources, but additional thermal insulation is needed to increase the energy efficiency and thereby significantly reduce the demand (Papadopoulos, 2005).

Fossil-based thermal insulation

Improving insulation of the current and future building envelope is being recognised as a key strategy to decrease the space heating demand of houses worldwide nowadays (Papadopoulos, 2005). Nonetheless, this result is a great need of insulation materials to insulate both the current and future building envelope (NIBE, 2019). Furthermore, thermal resistance requirements become stricter to comply with environmental standards and laws, which adds more pressure on the need of insulation material (NIBE, 2019). However, current thermal insulation is often made of synthetic materials which are generally seen as unsustainable due to their fossil carbon emissions during the production phase (Zhu, Kim, Wang & Wu, 2014). In line with the European market of insulation materials, the Dutch market is characterised by inorganic fibrous materials and organic foamy materials, and most Dutch houses are either insulated with PUR (polyurethane) foam or glass or rock wool (Papadopoulos, 2005; Van der Wal, Ebens & Tempelman, 1987). The choice for conventional insulation material is often dedicated to the relatively low cost of the materials, high insulation properties and easy application (Karamanos, Hadiarakou & Papadopoulos, 2005). The fossil-based synthetic materials are however not desirable in a future in which the aim is to move away from burning fossil fuels.

Bio-based insulation

New and more eco-friendly thermal insulators are therefore needed to equilibrate the trade-off between the reduction in energy demand for heating along with insulation materials and their related environmental impact. The use of bio-based insulation materials could be a strategy to meet energy and carbon reduction needs, and at the same time contributing to a sustainable building sector (Romano et al., 2018; La Rosa et al., 2014). In recent years there has been an increasing interest of the building sector in renewable raw materials of natural origin as kenaf, hemp and flax, where they are gaining interest because of their thermal characteristics and sustainability (Zampori, Dotelli & Vernelli, 2013).

Bio-based thermal insulation (often named *bio-based insulations* or *bio-insulations*) avoid the extraction and emission of fossil carbon by using feedstocks containing biogenic carbon and remove carbon from the atmosphere through plant photosynthesis. They often have a lower embodied energy compared to fossil-based insulation material (Figure 1), but the main advantage is the biogenic carbon stored in the material (Romano et al., 2018). However, a disadvantage mentioned by Romano et al. (2018) and La Rosa et al. (2014) is that bio-based materials often require more land to produce the material compared to fossil-based insulators. In high-population density areas as The Netherlands, attention should be paid to the available area for bio-based agricultural purposes, including bio-based thermal insulators (Breure, Lijzen & Maring, 2018). The competition for agricultural land has heightened between the available land for production of food, bio-material, bioenergy and forestry areas and other competing land uses, e.g. urbanisation and nature development (Diogo, Koomen & Kuhlman, 2014; Van der Hilst et al., 2010). It is therefore necessary to carefully consider which areas can be used for which purposes. One potential area for bio-based purposes might be peatlands, which are currently mostly used for dairy farming.

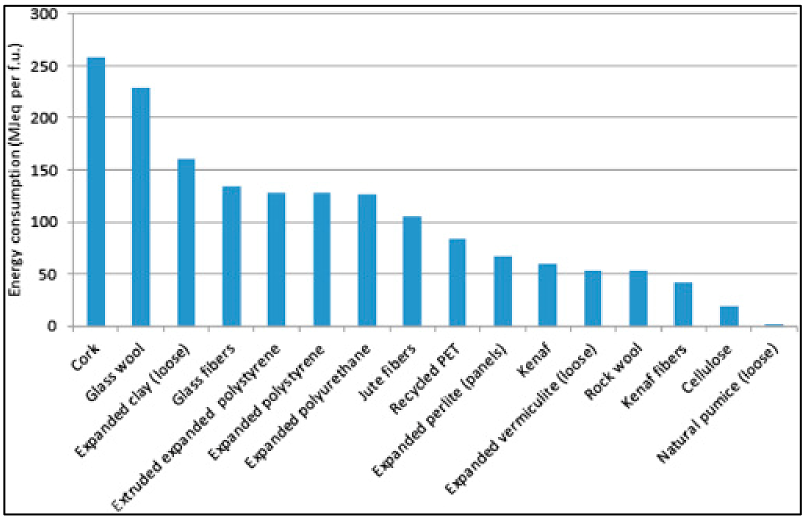


Figure 1: Energy consumption of different insulation materials per f.u. (=the mass in kg of material needed to have a value of thermal resistance equal to 1 m^2 K/W for a 1 m^2 panel), cradle-to-gate (Schiavoni, D'Alessandro, Bianchi & Asdrubali, 2016).

Land subsidence and greenhouse gasses from peatlands in The Netherlands

An emerging problem on peatlands is however the related land subsidence due to drainage for creating arable land (Wichtmann & Joosten, 2007). Peatlands are a type of wetland which contain large amount of organic, carbon-rich material, known as peat (Lunt, Fyfe & Tappin, 2019), and cover large areas of West- and North-Netherlands (Brouns, 2018). Many coastal peatlands have been drained in the past centuries to create arable land, but this drainage results in the physical compaction of peat. Its degradation leads to subsidence and oxidation reactions of the organic matter leads to emissions of CO_2, CH_4 and N_2O (Erkens, Van der Meulen & Middelkoop, 2015). This turnover forms a carbon sink into a carbon source has resulted in significant GHGs emissions globally, with an estimation of 1.91 (0.31-3.338) Gt CO_2.eq annually (Leifeld & Menichetti, 2018). Dutch peatlands are responsible for more than half of the amount of GHGs from agriculture, whereas they only cover less than 10 % of Dutch agricultural area (Fritz, Lamers, Van Dijk, Smolders & Joosten, 2014). It is estimated that there is approximately 270.000 ha of peatlands in The Netherlands (Bodemkaart, 2014), which results in approximately 3-5% of the total Dutch emissions from dewatering the peatlands, equivalent to 7 Mt CO_2 (Ekker, 2017). In principle, GHG emissions from peatlands will continue until dewatering of the peatlands is decided. In the Dutch Climate Agreement, a goal is set to reduce the emissions from Dutch peatlands with 1 Mton CO2.eq by 2030 (Urgenda, 2020).

Besides the ecosystem function of peatlands as a carbon sink, the disappearance of peatlands poses severe threats on other ecosystem services of peatlands as fibre and fuel production, freshwater provisioning and supporting services related to biodiversity and nutrient cycling (Kimmel & Mander, 2010).

Given this context, the current management practice on peatlands is under pressure as continuing with the drainage from peatlands leads to among others continuous land subsidence, increased GHGs as well as lower (ground) water quality and loss of biodiversity (Fritz et al., 2014). However, changing this practice is usually disadvantageous for farmers; when they stop draining areas, valuable land for dairy farming is lost. Farmers are only willing to adopt new sustainable practices if they are practical and financially viable and are therefore reluctant to adopt new sustainable practices (Wichmann, 2017; Van der Hilst et al., 2010). Changing the mindset of conservative farmers is difficult, but insights in new economic business models could contribute to this. Therefore, solutions are needed to combine (alternative) agricultural practices which are economically viable, thereby preserve the value of peatlands and preferably reduce the GHGs. One possible solution could be the further development of wet agriculture, also known as paludiculture (Wichtmann & Joosten, 2007).

***Paludicrops* as a result for these two emerging problems?**

Paludiculture (Latin “palus” means swamp) is seen as a possible alternative use for areas with a high groundwater level as peatlands. Paludiculture is wet agriculture (on among other peatlands) and holds the promise of combining both the reduction of GHGs from peatlands with continued land use and biomass production under wet conditions (Wichtmann & Joosten, 2007).

Rewetting peatlands could be a mitigation measure to counteract the GHGs from land-use (changes). The contribution of land use, land-use change and forestry (LULUCF) to climate change is gaining more and more visibility and therewith, interest is growing on policy options to reduce these difficult-to-mitigate LULUCF GHG emissions (Harper et al., 2018). Current land-based mitigation for Paris climate targets assumes significant land-use change to support large-scale CO_2-removal from the atmosphere by e.g. afforestation/reforestation, avoided reforestation, and Biomass Energy with Carbon Capture and Storage (BECCS) (Harper et al., 2018). Paludiculture might be an interesting option to induce land-based GHG mitigation.

Potential crops from paludiculture are for example cattail (bio construction material and insulation material), azolla (biodiesel), miscanthus (concrete, paper) hemp (textile, lime-hemp construction blocks) as well as fruits like berries (Van Duursen & Nieuwenhuijs, 2016). Although much is written about the potential of paludiculture (e.g. Schäfer, 2011; Wichtmann & Joosten, 2007; Karki, Elsgaard, Audet & Laerke, 2014; Wichmann, 2017), the market is still in its infancy.

One of the *paludicrops* is cattail, which is used for insulation purposes, which potential has been acknowledged in several literature studies (e.g. Geurts & Fritz, 2018, Bestman et al., 2019). Cattail has good insulation properties compared to fossil-based thermal insulators (Bestman et al., 2019). Previous research has shown that both the R-value (2.3-1.7 m^2 K/W), a measure of the resistance of an insulation material to heat flow, and the Lambda (0.044-0.061 W/m.K), a measure of the thermal conductivity of a material, are not inferior to fossil-based stone wool insulators (Bestman et al., 2019). Stone wool has an R-value of 2.5 m^2 K/W at a thickness of 10 cm and a lambda of 0.04 W/m.K.

However, switching towards paludiculture often implies drastic land use changes (Wichmann, 2017). These land use changes are mainly determined by economic variables (Buschmann et al., 2020). This is confirmed by Wichmann (2017), who states that land users only adopt sustainable practices as paludiculture if they are practical and financially viable. To conclude, the economics of wetland management are an important factor in the system change towards paludiculture.

Research gap and relevance of the research

There is an ongoing problem of land subsidence and related GHGs of peatlands, with peatland ecosystems disappearing. Additionally, there is a need for insulation material, which is ideally bio-based to meet energy and carbon reduction needs. Paludiculture holds the promise of being a solution for the two proposed problems and in this way contributing to a sustainable Dutch peat meadow area. This is needed, as stated by Smolders et al. (2019): “*there is an urgent need for new insights which can contribute to a sustainable landscape of the Dutch peat meadow areas and the conservation of these areas*.”

However, previous research has mainly focused on separate topics as the environmental performance of bio-based insulation and GHG emissions of (land use on) peatlands. The economic viability of a system change has been largely neglected in existing literature with no studies with reliable data available (Wichmann, 2017).

Nonetheless, insights in the cost-effectiveness of wetland management are needed to make a system change happening, with commercial viability as one of the key drivers as previously stated by Buschmann et al. (2020).

Nevertheless, combining all these elements and giving an integral overview of the role of paludiculture as a new method to counteract the problem of GHGs of peatlands, a solution to meet the insulation demands and to assess the viability of the system, has not been done before. To overcome the proposed research gap, there are three objectives of this research, namely:

1) Assessing the GHG reduction potential of an increased water level on peatlands,
2) Assessing the climate impact of the production of a cattail insulation plate,
3) Assessing the commercial viability of paludiculture, with and without carbon credits.

Regarding the first two aims, the climate impacts of two systems are researched. In the reference scenario, a hectare peatland is used for dairy farming and a mixture of insulation wool (glass and stone wool) is used as insulation material. In the alternative scenario, 1 hectare peatland is used for paludiculture with cattail to be used as insulation material, and dairy farming is replaced to set-aside farmland. Both scenarios include the GHG emissions of peatlands associated with the water level, in which the area is drained in the reference scenario, and the water level is elevated in the alternative scenario. In this way, optimisation of 1 ha agricultural land from a climate perspective is assessed in a system perspective, which has not been analysed before.

Overall, this leads to the following research question:

What is the potential of paludiculture-produced bio-insulation material from cattail from a climate and economic point of view?

With the related sub-questions:
SQ1: What is, from a climate perspective (CO_2.eq), the optimal system use of current peatlands?
- What is the climate impact (CO_2.eq) of the production of cattail insulation plates compared to a mixture of glass and stone wool?
- What is the GHG reduction potential (CO_2.eq) from rewetting peatlands, formerly used for conventional dairy farming?

SQ2: What is the commercial viability of paludiculture-produced insulation material compared to dairy farming and to what extent can carbon credits play a role in the viability?

SQ3 is linked with SQ2 by the addition of a carbon credit market, which is partly calculated with the GHGs reduction potential resulting from SQ1.

Thesis structure
This thesis consists of ten Sections. In Section 2, theory and background information is given regarding peatlands, the principles behind LCAs, paludiculture and economic viability of (agricultural) system changes. In Section 3 (Methodology: LCA), the methodology applied to assess the first aim is discussed. This part focusses on the methodology and assumptions in the performed Life-cycle Analysis (LCA) of cattail-insulation plates and the second one on the model to identify the GHG emissions resulting from peatlands with and without an elevated water level. In Section 4 (Methodology: Commercial viability of paludiculture) the methods to assess the competitiveness of growing cattail compared to current land use are discussed. In Section 5 (Intermediate results), the intermediate results regarding the functional unit are given. In Section 6, the results of the LCA are shown as well as the GHG reduction potential of peatlands. A system overview with related GHG emissions is given. In Section 7, the cost-benefit analysis is presented, in- and excluding valuing the GHG emissions by carbon credits. An estimation of the potential GHG benefits from a system change towards paludiculture on a larger scale in The Netherlands is given in Section 8. In Section 9 (Discussion), a sensitivity analysis is presented, limitations of the research and recommendations for future research are given. Lastly, Section 10 (Conclusion) gives an overview of the research, main results and answers to the research question.

2. Theory, concepts and case study description

In this Section, relevant theories and concepts are explained and existing knowledge is summarised. This implies knowledge about peatlands (e.g. land use, land subsidence and related GHGs) (Section 2.1) and information about the principles of an life-cycle assessment (Section 2.2). Moreover, information about conventional and bio-based insulation material is given, with production processes and related environmental performance (Section 2.3). In Section 2.4, basic information about the economic viability of system changes is given, with the related concepts as cost-benefit analysis and the carbon (credit) market. Finally, details about the case study are given with up-to-date existing literature on (viability of) paludiculture, cattail properties (Section 2.5).

2.1 Peatlands

2.1.1 General information about peatlands

Peatland ecosystems

A peatland is a type of wetland that occurs in almost every country and are ecosystems that contain large amount of decomposed organic material, known as peat. Peatland ecosystems are one of the most important ecosystems in the world, especially in terms of absorbing and storing carbon (Lunt et al., 2019). Its importance is illustrated by the fact that while covering only 3% of the world's land area, the soil organic carbon capacity of peat is 450 Gt C, which equals approximately one third of the world's soil carbon, although data differs and values as 612 Gt C are also mentioned (Parish et al., 2008; Yu et al., 2011 in Lunt et al., 2019). Moreover, peatlands have other varied identified ecosystem services and related ecosystem functions (Kimmel & Mander, 2010). For example, provisioning services are fibre and fuel production, food and freshwater provisioning. Regulating services are among other climate and water regulation, water purification and erosion protection. Additionally, cultural services are related to recreational and spiritual service, and supporting services related to biodiversity, soil formation and nutrient cycling.

The biochemical processes and carbon exchange in peatlands are quite unique. Whereas the definition varies, peat consists of a layer of roughly more than 30 cm or 40 cm of partially decomposed material with at least 60% of organic matter (OM) (Harpenslager, 2015). In the Netherlands, peat soils are defined as soils with more than 40 cm of material more than 15 % OM in the upper 80 cm.

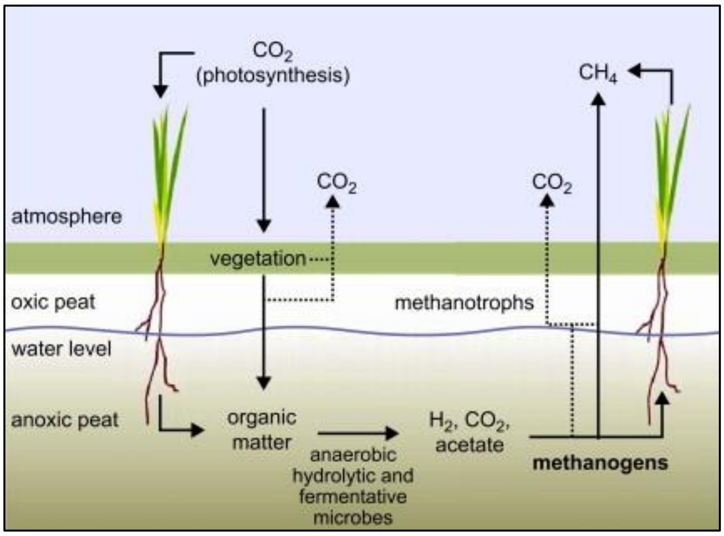


Figure 2: Peatland carbon exchange (Flores, 2014).

An illustration about the peat carbon exchange is provided in Figure 2 (Flores, 2014). Peatlands arise when net primary production exceeds the decomposition rate of organic matter, leading to the formation of peat in wet, acid conditions. Decomposition refers to the process of breaking down of complex OM into simpler inorganic compounds (Lunt et al., 2019). The decomposition rate is affected by biotic factors among other the quality of OM and the composition of soil organisms and by abiotic factors as climate, pH, oxygen availability and hydrology.

The nutrient cycle of peatlands and the interaction with the atmosphere is primarily through the gasses CO_2, CH_4 and N_2O (Limpens et al., 2008). The process of photosynthesis results in the sequestration of CO_2 in the atmosphere. Natural peatlands usually have a small (partly) oxic layer on top of the anoxic layer. Autotropic respiration of the plant tissues results in the formation of CO_2 and related CO_2-losses to the atmosphere (Limpens et al., 2008). Moreover, methanogenesis occurs in the anoxic layer, which is the process of forming methane by methanogens. This process is a dominant pathway for OM decomposition in wetlands due to the lack of other oxidants (Schlesinger & Bernhardt, 2013).

Peatlands in The Netherlands

Peat formation has taken place for ages in The Netherlands, and current peat areas in The Netherlands are seen in Figure 4. They cover an estimated amount of 270.000 ha (Bodemkaart, 2014). Two main type of peat are identified in The Netherlands, namely fen peatlands and bogs (Brouns, 2018). Fens receive base-rich water that has been in contact with mineral soils, whereas bogs only receive water from precipitation. The related tropic status depends on the amount of available minerals, eutrophic refers to nutrient-rich (fens), mesotrophic is semi nutrient-rich and oligotrophic is nutrient-poor (bogs). Most peatlands areas in The Netherlands are mesotrophic, and then eutrophic (Rienks & Gerritsen, 2005).

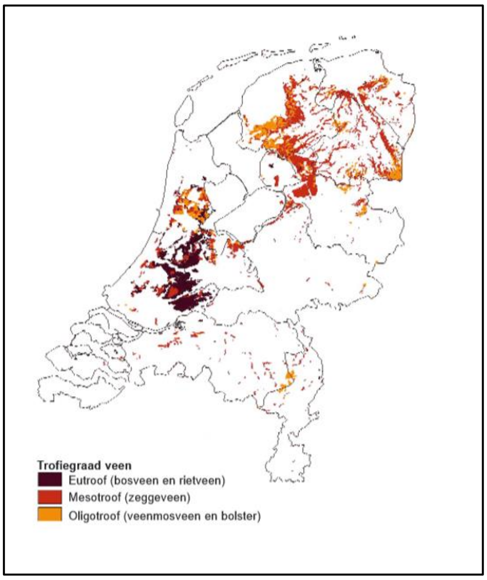


Figure 4: Peatland areas in The Netherlands (Rienks & Gerritsen, 2005).

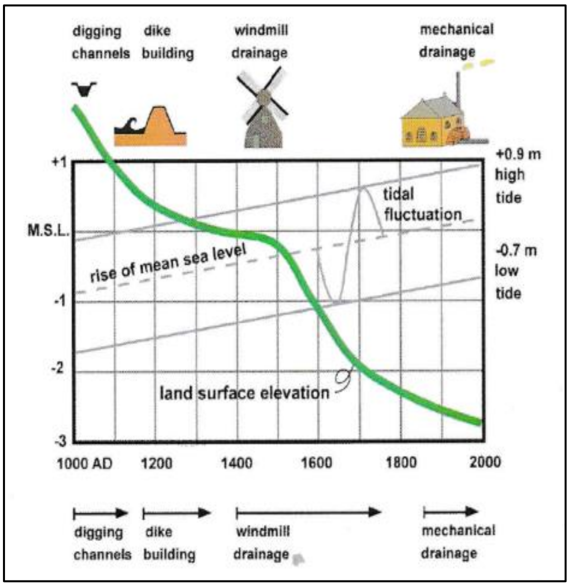


Figure 3: History of land subsidence and sea level rise (Van de Ven, 1993 in Brouns, 2016).

Natural threats were the major reason of peat formation reduction for a long time, but from the fifth century, peatlands were used for extensive grazing and thereby reducing peat accumulation (Brouns, 2016). However, the rise in human population (from the Middle Ages onwards) resulted in two main land management changes, namely the increase in drainage and the excavation of peat (Rienks & Gerritsen, 2005).

In the need for reclaiming areas for agricultural purposes as extensive grazing, drainage was applied in peatlands. At first, this was done by digging ditches and controlling the water level, but the invention of windmills drastically improved the drainage management (Brouns, 2016). The windmills were used to pump the water out of the already low polders to external reservoirs, thereby boosting the drainage efficiency and agricultural production (Erkens et al., 2016). The problem of this decreasing (relative) land surface elevation has increased along with the continuing improvement of drainage managements (Figure 3).

Accompanied together with the rising population, there was a growing demand for fuel to keep up with industrialisation and urbanisation. The highly calorific peat was a good replacement for the scarcity of wood (Harpenslager, 2015). This burning of peat resulted in the excavation of large areas, thereby creating deep lakes and resulting in high subsidence rates.

Both the extraction of peat and the drainage management has resulted in a decreasing land surface elevation in relation to the rise of the mean sea level. This decline of peat soils is still ongoing, mainly due to intensive drainage (Erkens et al., 2016).

2.1.2 Land use on peatlands

Most Dutch peatlands are currently used for intensive agriculture and need to be drained (Rienks et al., 2002). Dairy farming is the main land use in the northern and western peat areas, together with a small production of flower bulbs, maize and sugar beets on thinner peat areas in the province of Drenthe (Brouns, 2016; Rienks et al., 2002).

Dairy farming on peatlands suffers from different challenges as the wet soil, poor carrying capacity and increasing costs of drainage (De Vos, Van Bakel, Hoving & Smidt, 2010). Dairy farming demands deeper groundwater levels and therefore permanent drainage to have favourable working and grazing conditions (De Vos et al., 2010). Furthermore, to increase production, the agricultural areas are often fertilised and (a surplus of) manure is applied, which results in the accumulation of phosphorus (P) and nitrogen (N) (Harpenslager, 2015). This increase in nutrient concentrations along with the increased atmospheric deposition of N results in the change of the peatlands from mainly mesotrophic to more eutrotrophic. Where at first peat-growing species live in the peatlands, this changes into fast-growing but also fast-decomposing species that inhibit the peat growth, contributing to land subsidence.

It can be expected that an economic and sustainable dairy farming on peatland meadows is difficult soon. However, changing the current land management is difficult (De Vos et al., 2010). Dairy farming is seen as the traditional agriculture on Dutch peatlands and rural economies need to be revitalised by combining traditional land use with new ways of processing (Wichtmann & Joosten, 2007).

2.1.3 Land subsidence and related greenhouse gas emissions (GHGs)

In Figure 5, it can be seen that the draining in the northern part is deeper, with drainage depths of 90 cm or more. Shallower groundwater levels occur in the western part, with approximately 30-60 or 60-90 cm or more (Van den Born et al., 2016). The most common drainage category is 30-60 cm (34%), followed by >90 cm (21%) and 60-90 cm (19%) (Van den Born et al., 2016).

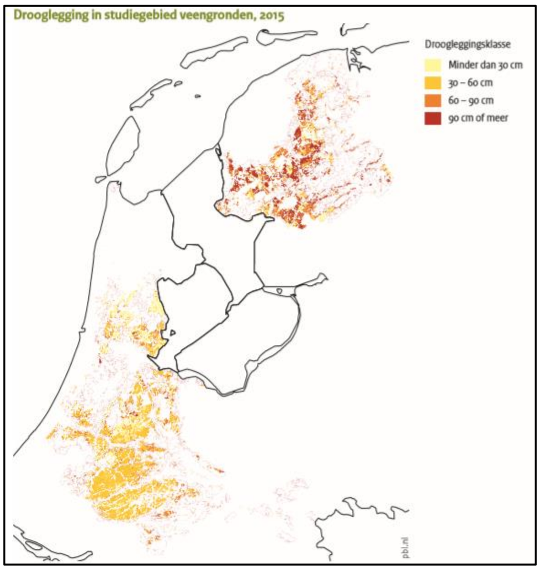


Figure 5: Drainage depths (Van den Born et al., 2016).

The increased aeration from drainage causes peat to shrink and oxidise (aerobic decomposition), which results in volume reduction and related GHG emissions. It is known that peat compresses when loaded, which results in an even further volume reduction and subsidence. This shrinkage is largely irreversible and rehydrated peat will not regain its initial volume, leading to high subsidence rates (Erkens et al., 2016). It is estimated that up to 60-85% of the subsidence can be attributed to decomposition (Brouns, 2016). The subsidence rates vary in literature, but an average of 6-12 mm per year is often mentioned, depending on the local groundwater depths and peat characteristics (De Vos et al., 2010).

The oxidation process also results in the release of significant GHG emissions (CO_2, N_2O and CH_4). When air can enter deeper into the ground (drainage), the organic material is broken down in a reaction with oxygen and CO_2 is released in the air (Rienks & Gerritsen, 2005). Along with the process of methanogenesis, this results in high levels of GHG emissions resulting from peatlands.

Dutch peatlands are responsible for more than half of the amount of GHGs from agriculture, whereas they only cover less than 10 % of Dutch agricultural area (Fritz et al., 2014). The water management, type of land use and management determine the amount of GHG emissions released (Van den Born et al., 2016), together with peat soil characteristics (De Vos et al., 2010). Concerning the rise of the water level, Van den Born et al. (2016) state that a peat soil subsidence of 1 cm equals approximately 22 tons of CO_2 per hectare, thereby not mentioning CH_4 and NO_2 emissions. Fritz et al. (2014) also mention numbers in the same order of magnitude: An hectare dewatered peatland has an average emission of 20-25 t CO_2.eq annually, depending on the groundwater level and the drainage level. It is estimated that approximately 3-5% of the total Dutch emissions is resulting from dewatering the peatlands, equivalent to 7 million t CO_2.eq annually (Ekker, 2017; Van den Born et al., 2016). In the Dutch Climate Agreement, a goal is set to reduce the emissions from Dutch peatlands with 1 Mton CO2.eq by 2030 (Urgenda, 2020).

2.1.4 The future of peatlands

With the transformation of peatlands from net carbon sinks to carbon sources, the increased CO_2 levels and the important services provided by wetlands, it is needed to preserve the wetland ecosystems.
However, the current trends show that there is a large decrease of wetlands, with more than half of the worldwide wetlands lost, drained or degraded (Davidson, 2014). The increase of human-made wetlands (reservoirs, aquaculture ponds or rice paddies) is relatively small compared to the natural wetlands with an average long-term loss of 54-57% (Davidson, 2014). The same trend is observed in The Netherlands: each year 2000 ha peatlands is lost, with an overall reduction of 20% of the Dutch peatlands in the last 30 to 40 years (Rienks et al., 2002). If the management practices in the peatlands areas is continuing in a *business as usual*-scenario, Rienks et al. (2002) estimate that the Dutch peatlands will disappear in the next 500 years, with even the disappearance of the major part in the coming 200 years.

Another (human-induced) threat to peatlands is climate change. Several studies have been performed about the influence of climate change in peatlands (e.g. Querner, Jansen, Van den Akker, Kwakernaak, 2012; Heijmans, Mauquoy, Van Geel & Berendse, 2008; Brouns, 2016). All conclude that the temperature increases, and summer droughts will enhance peat decomposition. Summer droughts can result in secondary decomposition. This process of enhanced decay of peat in deeper normally-water saturated layers occurs when there is a drop of summer water tables due to the high evaporation losses of peat meadows. As a result, deeper peat layers are exposed to oxygen and become aerated, resulting in GHGs.

It is needed to preserve peatlands now and in the future. Preserving wetlands can be done by conserving, restoring or construct carbon-storing wetlands (Overbeek, 2019). Paludiculture is a form or rewetting peatlands and therefore a way to restore the carbon sink function of wetlands (Overbeek, 2019). The idea of paludiculture is explained in Section 2.5.1.

2.2 Life-cycle Assessment (LCA)

2.2.1 LCA principle

Information on environmental aspects of systems is needed to be able to integrate environmental considerations into decision-making. Different tools have been developed of which the Life-cycle Assessment (LCA), Environmental Risk Assessment, Material Flow Analysis and the Ecological footprint are examples (Finnveden et al., 2009). One tool is the proposed Life-cycle Assessment (LCA), which assesses the potential environmental impacts and resources throughout a product's life-cycle. This implies the raw material acquisition, via production and use phases, and different waste management options as disposal and recycling. It is therefore also known as life-cycle analysis, eco-balance and cradle-to-grave analysis. The LCA-approach is considered as a holistic methodology which contributes all attributes or aspects of the ecological well-being, human health and resource depletion (Singh et al., 2010).

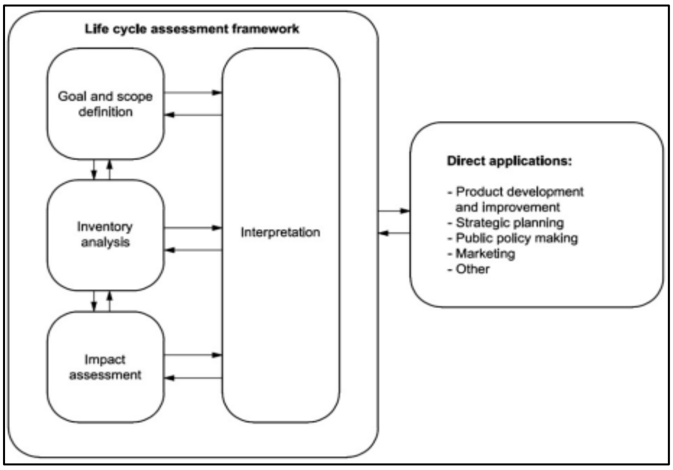


Figure 6: The LCA-framework (ISO, 2006).

An LCA-study implies four phases and is practiced according to the international standards in the International Organisation for Standardisation (ISO)14000:2006 series. The four phases are goal definition and scoping, life-cycle inventory analysis (LCI), life-cycle impact assessment (LCIA) and interpretation

(Finnveden et al., 2009; Singh et al., 2010). The LCA-framework is depicted in Figure 6. The four stages are explained in the following paragraphs.

Stage 1: Goal and scope definition

The first stage is the goal, scope and the functional unit definition of the study. Identifying the goal of the study naturally flows into thinking of the intended application and the intended audience of the study.

Additionally, all processes and related impacts are normalized with respect to a quantity named a functional unit (f.u.). The f.u. is the reference unit through which a system performance is quantified and enables a comparison between two essential different systems (Asdrubali, D'Alessandro & Schiavoni, 2015). The f.u. must be expressed in terms of per unit output (for example kWh or km basis) and should therefore focus on the product function, rather than on the production or consumption volumes (Baumann & Tillmann, 2004).

Moreover, the initial system boundaries are identified. Initial boundaries of the system are determined by the goal and the scope of the analysis. The complete cycle can be analysed (*cradle to grave*): from raw material to production and use phases to waste management (either disposal or recycling) (Asdrubali et al., 2015). The *cradle to gate* approach is used when the assessment of the product ends before the transportation to the customers.

Lastly, an appropriate LCA method should be chosen, depending on the purpose of the study, which is either attributional or consequential. An attributional LCA aims to describe all the relevant environmental flows in a complete life-cycle. A consequential LCA also describes these flows, but also aims to describe how these flows will change as a consequence of adding or removing an activity (Figure 7).

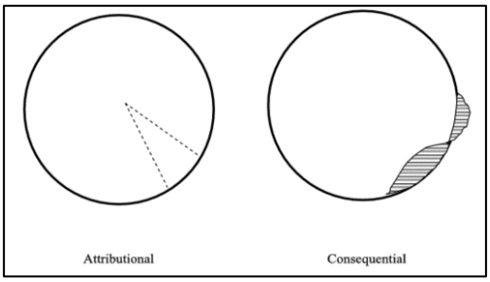


Figure 7: The conceptual difference between attributional and consequential LCA (Weidema, 2003).

The choice of an LCA-method is rather important as it influences system boundaries related to allocation (see Stage 2) and it can influence other methodological choices as the definition of the f.u. and the choice of the LCIA (see Stage 3) (Rebitzer et al., 2004). For example, Lundie et al. (2007 in Finnveden et al., 2009) argue that when support of decision-making is the purpose. Ekvall, Tillman & Molander (2005) states that both methods can be used for decision-making, with attributional LCA more valid in avoiding connections with systems with large environmental impacts. Consequential LCA is more valid to assess individual rules or decisions and its related environmental consequences.

Stage 2: Life-cycle Inventory analysis (LCI)

The second stage is the inventory of all life-cycle steps and data in relation to its f.u. and gives a compilation of the inputs (resources) and outputs (emissions) over the life-cycle. Data sets need to be collected, which can be done among others through public, national or regional LCI-databases as European Reference Lifecycle Database, or commercially available LCA-software as Agri-Footprint (Finnveden et al., 2009). Afterwards, data can then be organised in manual sheets or organised in dedicated software. Besides this initial data collection, system boundaries need to be refined because of the ex- or inclusion of sub-systems, material flows and new unit process, which will be explained subsequently.

Within the LCI, there are several major types of system boundaries (Guinée et al., 2002; Tillman, Ekvall, Baumann & Rydberg, 1994). The first three are the major types, according to Guinée et al. (2002), but Tillman et al. (1994) mention two additional boundaries, namely geographical and time limits.

- **Boundaries between the technological system and nature.** This refers to the whole life-cycle, starting with the extraction of raw material to the final stage (waste generation/heat production). The activities needed to bring the resources in the technological system should be included. For example, for biological resources, the harvest should be included as well as the activities to produce the harvest as planting, fertilizing and the use of pesticides.

- **Boundaries between the current life-cycle of the studied product and related life-cycles of other products.** Boundaries must be set between the life-cycle of the product studied and other associated life-cycles as most activities in the global technological system are interrelated. Product systems are usually interrelated in a complex way and independently analysing all the single life-cycles can then result in an endless flow of in- and outputs. Therefore, some parts must be excluded, but this does alter the output of the study. This boundary will be further elaborated in the paragraph *'Multi-functional processes.'*
- **Between significant and insignificant processes.** This system boundary is rather difficult as beforehand, the distinction between significant and insignificant processes and data is unknown. However, this system boundary is more focused on optimisation of the LCA. At first, easily accessible data can be obtained, the importance and validity can be checked, and the data can be refined if needed and possible. In this way, the LCI and the LCIA is performed in iterative loops until the required precision has been achieved.
- **Geographical area and time horizon.** An LCA should be geographically restricted and accompanied with a time horizon. Geography can play a role in LCAs in for example infrastructure (as electricity production or waste management) can differ in different regions as well as the sensitivity of the ecosystems in response to environmental impacts or pollutants. The purpose of LCAs is to identify the present and predicted future impact of e.g. a production process or consumption goods. The limitations of time refer to the lifetime of pollutants and the timespan of the involved technologies.

Multi-functional processes

Multi-functional processes can occur when a process is shared between several product systems. Multi-functional processes can either be multi-output (one process produces several products), multi-input (one process receives several products) or open-loop recycling (one waste product is recycled to another product) (Finnveden et al., 2009).

When performing an LCA, there is a major issue on how to deal with multifunctional processes and recycling. Generally, there are two different ways of handling multi-functional processes, namely allocation and system expansion (Ponsioen, 2015). The first one refers to allocating the environmental impacts of products based on physical and chemical principles, economic values or a physical parameter as energy or mass. The latter one, system expansion, approaches the allocation problem by avoiding it. The processes are divided into subprocesses or expanded and include affected parts of other life-cycles. Assumptions are made about the so-called avoided burdens (Ponsioen, 2015; Weidema, 2018), related to an in- or decrease in output of the by-product and its environmental impact. This can be best explained with the example of beer. The production of beer delivers two products: the production of straw and spent grains, next to the main product beer. This straw and spent grains can be used as animal feed and with this production, the impact of producing other sources of animal feed is then avoided. Moreover, recycling of the beer can result in a reduction of the impact of virgin aluminium production. The system is expanded to include the additional functions related to the co-products. Therefore the term *substitution method* is also used, as the expansion is done by including the system that is substituted (avoided) by the dependent co-product (Figure 8) (Weidema, 2018).

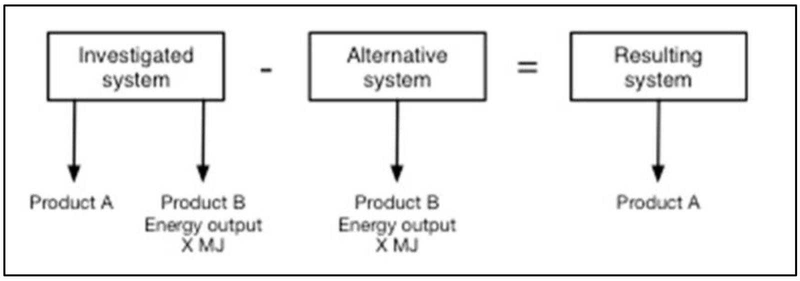


Figure 8: Avoiding allocations at multifunctional processes (Weidema, 2018).

The choice of allocation method has a major impact on the results (Ekvall & Finnveden, 2001). According to Rebitzer et al. (2004), the ISO recommends that if possible, allocation should be avoided either through the division of the whole process into sub-processes or by expanding the system with the *substitution method*. When allocation cannot be avoided, the second preference is partitioning of the in- and outputs based on physical relationships as mass, volume, energy or carbon content. The least preferred option is allocation based on other principles as economic values, mass or energy. This preference for system expansion to avoid allocation problems is not uniformly accepted in literature and critical reviews are written about the allocation principles in the ISO-standards (Ekvall & Finnveden, 2001). For example Lundie et al. (2007, in Finnveden et al., 2009) state that new allocation problems are likely to occur when the system is expanded, and Heijungs & Guinée (2007) mention the large uncertainties involved and the lack of data on what is to be avoided.

Stage 3: Life-cycle impact assessment (LCIA)

This stage aims to evaluate the significance of the potential environmental impacts based on the life-cycle impact flows. An LCIA conform ISO-standards consists of the following mandatory elements (Singh et al., 2010):

- **Selection of impact categories and classification***:* This step involves the identification of the categories of environmental impacts relevant to the study. There is no standardised list of impact categories and examples of environmental impact categories are global warming, eutrophication, ozone depletion, acidification of soil and water, human/freshwater aquatic ecotoxicity and water pollution. The emissions from the inventory phase are assigned to the impact category and thereby their ability to contribute to environmental problems (Finnveden et al., 2009).
- **Selection of characterisation***:* The impact of each emission is modelled quantitatively and expressed as an impact score in a unit related to the impact category. For example, CO_2-equivalents are used as a proxy for GHGs contributing to the impact category climate change, kg PO_4^{3-}-equivalents for eutrophication and kg CFC-11-equivalents for ozone depletion. Moreover, the potential impact of each substance in terms of the common unit of the category is characterised. For example, the global warming potential (GWP-100) is an often-used characterisation factor for climate change. As this indicator is used in the proposed research, more information is given about the GWP and other characterisation factors are disregarded, but additional information can be found in Singh et al. (2010). To account for different GHGs (not only CO_2) and their related global warming potential, the GWP-approach has been developed as a standardisation metric to compare different GHGs relative to CO_2, which has the value of 1, expressed in CO_2.eq (Morawicki & Hager, 2014). A GWP is calculated over a specific horizon which are commonly 20, 50 or 100 years. This horizon greatly affects the GWP characterization factor, because a gas can have a large short-term effect, but could have less effect on the long-term (Fearnside, 2002). The best gas to illustrate this is methane (CH_4); its characterization factor is 86 and 34 for 20- and 100-years horizon, respectively. So, the short-term effect of CH_4 is almost 2.5 times larger than the GWP with a 100-year horizon. Therefore, mentioning the reference when quoting a GWP is crucial. Commonly, a time horizon of 100 years is used by regulators.

There are two possible additional elements, but these are not mandatory according to the ISO standard on LCA (Finnveden et al., 2009). These are normalisation (relative weighting to a reference value) and weighting/grouping (relative weighting to each other). However, there is no objective way to perform weighting as it is dependent of the application of preferences. Therefore, the ISO-standard generally advises against weighting (Finnveden et al., 2009).

Stage 4: Interpretation

At the last stage, the results of the previous phases are analysed in relation to the goal and scope. An LCA is considered to be a holistic methodology, but nevertheless, uncertainties can remain in among other data collection, choices in system boundaries or allocation principles and relations, with for example the assumption of a (non-)linear relationships of GHGs. Therefore, the main focus in the interpretation phase is to determine the level of confidence and communicate them in an accurate, fair and complete way (Singh et al., 2010).

According to Singh et al. (2010), sensitivity analysis is proposed to be a systematic evaluation process for describing the effect of variations within a study. The analysis can be carried out in three ways, i.e. data uncertainty analysis, different system boundaries and different life-cycle comparisons (Finnveden et al., 2009).

The final step of the interpretation phase is to give conclusions, limitations and recommendations, considering the previous outcomes of the sensitivity analyses.

2.2.2 Biogenic carbon storage and delayed carbon emissions in LCAs

Bio-based products store a great amount of carbon and this storage could potentially be used to delay emissions and gain carbon credits (Pittau, Krause, Lumia & Habert, 2018). During growth, there is an intake of carbon which is temporarily stored in bio-based products (biogenic carbon storage). This could lead to positive long-term effects when the carbon is stored in the anthroposphere before released again in the atmosphere after a long-time span. When the stored carbon is left out of the atmosphere for a certain period, the effect of the global warming is postponed (Garcia & Freire, 2014). Pawelzik et al. (2013) state that carbon uptake is one of the major environmental benefits when considering fibre-based material. Zampori et al. (2013) state that the carbon uptake should indeed be taken into consideration (regardless of the end of life- scenario) and if the use phase is longer than 10 years. This however should be explicitly specified and mentioned.

There are however several critical issues associated with this storage of carbon and the related the life-cycle of wood-based products, particularly regarding the calculation of the carbon footprint (Garcia & Freire, 2014). In general, wood-based products have a relatively long service life in which they store carbon and delay the carbon emissions in both the use and disposal phase. The delayed emissions results in issues when carbon footprints of products are determined, as there is an indifference to the time scale. Within traditional LCAs, past, present and future emissions are treated equally and integrated over time, and it is often assumed that the biological uptake during growth and release in the end-of-life phase cancel each other out (Wijnants, Allacker & De Troyer, 2019). A lot of research has been performed in the past years on carbon footprinting, but there is yet no consensus on the possible benefits of biogenic carbon sequestration, temporary storage or delayed emissions (Wijnants et al., 2019). However, it is increasingly acknowledged that the biogenic CO_2 should be considered. There are different carbon footprint approaches, which all have different assumptions and approaches to these issues and therefore greatly influence results (Garcia & Freire, 2014). There are, for example, dynamic methods as proposed in Levasseur et al. (2013 in Wijnants et al. 2019) which consider a consistent assessment of emission flows and radiative effects, or methods based on the global carbon cycle and land-use change (Vögtlander, Van der Velden & Van der Lugt, 2014). Another methodology is the Publicly Available Specification (PAS2050) which provides a method for assessing lifecycle GHG emissions and how to deal with biogenic carbon storage.

The PAS2050 builds on the existing standards for LCAs. In the PAS2050, the part of the removed (stored C) not emitted to the atmosphere during the 100-year assessment period is tread as stored C. Therefore, all emissions except from the use and disposal phase are treated as single emissions at the beginning of the 100-year period (Garcia & Freire, 2014). Carbon stored in wood products within 100 year is excluded from the footprint but may be separately documented as emitted in longer time periods and if so, a negative CO_2.eq is assigned to stored or fixed carbon.

Moreover, the use of a weighting factor is optional to calculate the effect of delayed emissions in the use and end-of-life phase and therefore accounting for the relatively long use phase (Garcia & Freire, 2014). This weight factor can be calculated with Equation 1, with *i* referring to the storage of the biogenic plates in years.

Equation 1: Calculation of weight factor in PAS 2050.

$$WF = \frac{\sum_{i=1}^{100} x_i \; \times (100 - \mathrm{i})}{100}$$

To illustrate the effect of this weight factor, a wooden house can be used as an example. Imagine a wooden house with an emission of 140 t CO_2.eq in the production phase (taken carbon storage into account), an emission of 250 t CO_2.eq in the use phase over 70 years and 60 t CO_2.eq at the end-of-life. The calculated weight factors are 1.0, 0.645 and 0.3 for the production, use and end-of-life phase, respectively. Without taken into account the delayed effect, this results in a total emission of 450 t CO_2.eq during the lifecycle of the wooden house. However, when the delayed effect is considered, this results in an emission of 320 t CO_2.eq and is considerably lower.

However, the methodology of the PAS2050 also has caveats. The underlying assumptions, as the 100 year assessment period can be seen as rather arbitrary as a thorough understanding of the fate of the product is required over a period of 100 years. In innovative, bio-based material, this is sometimes (yet) unknown. For example, Zampori et al. (2013) exclude the disposal phase from hemp insulation boards as there are numerous possible scenarios and assuming the right one is difficult. Another side note to mention is that care should be taken if a significant amount of non-CO_2 emissions are involved. The methodology of PAS2050 were developed specifically for CO_2-emissions and the result could be less accurate (Garcia & Freire, 2014).

2.3 Insulation material and properties

2.3.1 Conventional insulation

According to Karamanos et al. (2005), the European insulation market is characterised by inorganic fibrous materials (glass and stone wool), which account for 60% of the market, and organic foamy materials (expanded and extruded polystyrene and polyurethane) which account for some 27% of the market. These materials obtained from either petrochemicals (polystyrene) or natural sources processed with high energy (glass or stone wool) are nowadays commonly utilized as building materials. Two conventional materials are explained in detail, which are glass and stone wool, as they are used as reference insulation material in the research. More information about other types of conventional insulation and their production processes can be found in Schiavoni et al. (2016).

Stone wool

One of the main advantages of stone wool is that they can be used in very high temperatures up to 600 °C (Karamanos et al., 2005). Stone wool is manufactured by melting of rocks at a high temperature of 1600 °C. These melted rocks are then bound together using binders which are usually resins (Schiavoni et al., 2016) which increase the fibres' cohesion and the material stiffness (Karamanos et al., 2005). During the final step, the material is pressed to obtain the plat form. The production process of stone wool is shown in Figure 9. At the end-of-life, stone wool can be recycled by the producing manufacturers or disposed into landfills (Karamanos et al., 2005).

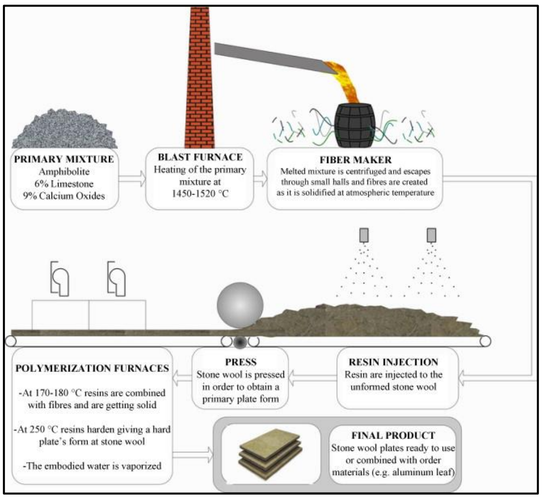


Figure 9: Production process of stone wool (Karamanos, Hadiarakou & Papadopoulos, 2005).

Stone wool has good thermal conductivity ranges (Table 1) and due to its inorganic material, they are incombustible and therefore applicable in a broad spectrum of applications. Moreover, Schiavoni et al. (2016) state that stone wool is a good sound absorber. These advantages, combined with the cheap price and easy use of the plates, are often-mentioned advantages to choose for stone wool.

Glass wool

Glass wool is produced by mixing natural sand and glass (usually recycled) at 1300-1450 °C (Schiavoni et al., 2016). Due to the process of centrifugation and blowing, fibres are formed which are bound together by a resin. Many small pockets of air are formed between the glass, which results in high thermal insulation properties, similar to those of stone wool (Table 1). However, this production process results in a high embodied energy (Table 2). Recycling of the used glass wool can be done by producing manufactures (Schiavoni et al., 2016).

Table 1: Thermal insulation performance of stone and glass wool (Schiavoni et al., 2016).

MATERIAL	DENSITY (KG/M^3)	THERMAL CONDUCTIVITY (W/M.K)
Stone wool	40-200	0.033-0.040
Glass wool	15-75	0.031-0.37

One disadvantage from inorganic fibrous material is that they are affected by wetness (Karamanos et al. 2005). The hydrophilic nature of the material allows for water absorption and can increase the thermal conductivity factor, thereby influencing the thermal properties of the material.

2.3.2 Bio-based insulation

Bio-based insulation as cotton, hemp, flax and wood are often seen as an alternative to thermal insulations based on non-renewable resources (Palumbo, Lacasta, Giraldo, Haurie & Correal, 2018). The use of bio-based material has multiple advantages as stated by Nguyen, Grillet, Bui, Diep & Woloszyn (2018): they are environmentally friendly, renewable, low in costs and minimize energy consumption. Natural fibres have a low density, high porous structure, low environmental impact and low thermal conductivity. The last advantage mentioned is their hygrothermal performance, which is beneficial for humidity control and indoor air quality, confirmed by Palumbo et al., 2018).

The global warming potential (kg CO_2.eq/f.u.) and the energy consumption (MJ/f.u.) are often-used categories to compare insulation material from an environmental point of view. According to Asdrubali et al. (2015), the evaluation of thermal insulation material is usually done by comparing the mass of material needed to obtain a thermal resistance of 1 m^2 K/W. The carbon footprint of the production of cattail insulation plates is therefore considered with a f.u. of the mass (kg) of insulating board which involves a thermal resistance *R* of 1 (m^2 K/W), calculated with Equation 2 (Ardente, Beccali, Cellura & Mistretta, 2008):

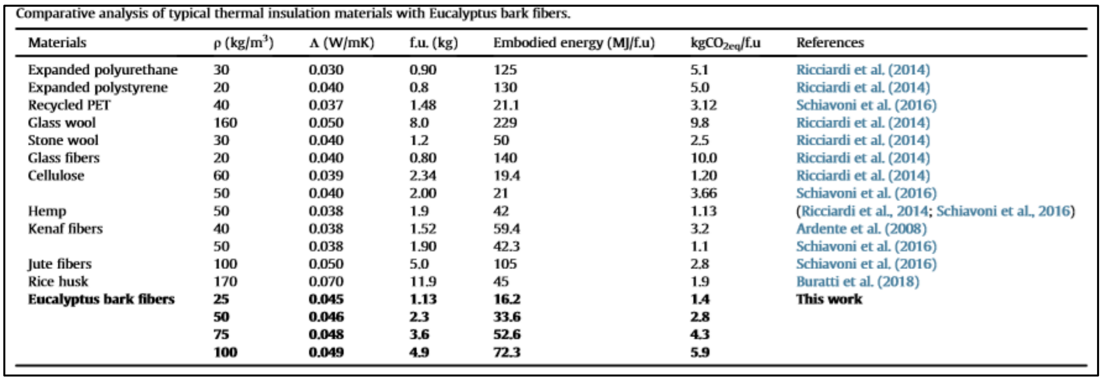
Equation 2: Calculation of the functional unit for insulation material.

$$f.u_{cattail\_board}. = R * \lambda * \rho * A$$

where *R* is the thermal resistance of 1 m^2 K/W, λ the thermal conductivity measured as W/ (m.K), ρ the density of the insulation product in kg/m^3; A is the area, 1 m^2. This f.u. gives information about the amount of insulation required to achieve a thermal resistance during the insulation lifetime.

An elaborated study of Casas-Ledón, Salgado, Cea, Arteaga-Pérez & Fuentealba (2020) about innovative insulation panels showed a comparative analysis of different thermal insulation panels and is given in Table 2.

Table 2: Analysis of thermal insulation material (Casas-Ledón et al., 2020).



Comparative analysis of typical thermal insulation materials with Eucalyptus bark fibers.

Materials	ρ (kg/m^3)	Λ (W/mK)	f.u. (kg)	Embodied energy (MJ/f.u)	$kgCO_{2eq}$/f.u	References
Expanded polyurethane	30	0.030	0.90	125	5.1	Ricciardi et al. (2014)
Expanded polystyrene	20	0.040	0.8	130	5.0	Ricciardi et al. (2014)
Recycled PET	40	0.037	1.48	21.1	3.12	Schiavoni et al. (2016)
Glass wool	160	0.050	8.0	229	9.8	Ricciardi et al. (2014)
Stone wool	30	0.040	1.2	50	2.5	Ricciardi et al. (2014)
Glass fibers	20	0.040	0.80	140	10.0	Ricciardi et al. (2014)
Cellulose	60	0.039	2.34	19.4	1.20	Ricciardi et al. (2014)
	50	0.040	2.00	21	3.66	Schiavoni et al. (2016)
Hemp	50	0.038	1.9	42	1.13	(Ricciardi et al., 2014; Schiavoni et al., 2016)
Kenaf fibers	40	0.038	1.52	59.4	3.2	Ardente et al. (2008)
	50	0.038	1.90	42.3	1.1	Schiavoni et al. (2016)
Jute fibers	100	0.050	5.0	105	2.8	Schiavoni et al. (2016)
Rice husk	170	0.070	11.9	45	1.9	Buratti et al. (2018)
Eucalyptus bark fibers	**25**	**0.045**	**1.13**	**16.2**	**1.4**	**This work**
	50	**0.046**	**2.3**	**33.6**	**2.8**	
	75	**0.048**	**3.6**	**52.6**	**4.3**	
	100	**0.049**	**4.9**	**72.3**	**5.9**	

Overall, it can be concluded that the thermal properties of traditional insulation fibres (expanded polyurethane, expanded polystyrene and glass fibres are better than the natural-based ones, but this is accompanied with a higher embodied energy. Although values on the embodied energy differ, it can be concluded that in general, natural fibre insulation materials (hemp, kenaf, rice husk and eucalyptus bark) show a lower energy demand (16.2-72.3 MJ/f.u.) and carbon emissions (1.1-5.9 kg CO_2.eq/f.u.) than traditional materials (50-229 MJ/f.u. and

2.5-10 kg CO_2.eq/f.u.). However, there should be mentioned that some traditional materials (stone wool, recycled PET) present lower embodied energy and global warming potential than natural ones. This might be due to uncertainties in input parameters, system boundaries, technology efficiency and completeness of the studies.

Significant carbon emissions in the lifecycle of natural fibre production are associated with fibre harvesting and panel production method. Fertilizer is needed in the harvesting phase, and additional synthetic fibres in the panel production phase. In the research of hemp insulation of Zampori et al. (2013), the indicator Greenhouse gas protocol (CO_2.eq) is used. The study revealed that panel production is responsible for 4.45 kg CO_2.eq, which is significantly more than the production phase of hemp (0.428 kg CO_2.eq), transport and scutching (0.131 kg CO_2.eq) and transport to panel production site (0.067 kg CO_2.eq). The addition of polyester fibre is a large contributor in this panel production, as it is responsible for 3.15 kg CO_2.eq.

When bio-based material is used for insulation purposes, additional products as a synthetic binder as polyester are usually necessary, as well as a flame retardant due to the high lignocellulosic fraction of bio-based products, and fungicide (Lazko et al., 2013). Polyester is often used as a binder (e.g. Zampori et al., 2013; Ardente et al., 2008). Often, flame retardants need to be added due to enhanced flammability of the material and further additives against fungal decay (Uihlein, Ehrenberger & Schebek, 2008). Uihlein et al. (2008) performed an LCA about insulation material from miscanthus and assume polypropylene as binder (14%), borax and sodium carbonate (in equal amounts) as flame retardant (3.5%) and thiocarbamate as fungicide (0.5%).

Moreover, system boundaries made in including the panel disposal could also affect carbon emissions (Ardente et al., 2008). There are several potential end-of-life scenarios for natural fibres, which are summarised in Figure 10 (Norton, Murphy, Hill & Newman, 2009). Following from the waste hierarchy, the first preference on how to deal with waste is prevent it, after which subsequently reuse, recycle, recovery and disposal are mentioned as preference steps in the waste hierarchy. Within the bio-based economy, it is aimed to shift from a *cradle-to-grave* approach towards a *cradle-to-cradle* principle with more reuse and recycling, thereby adhering to the waste hierarchy.

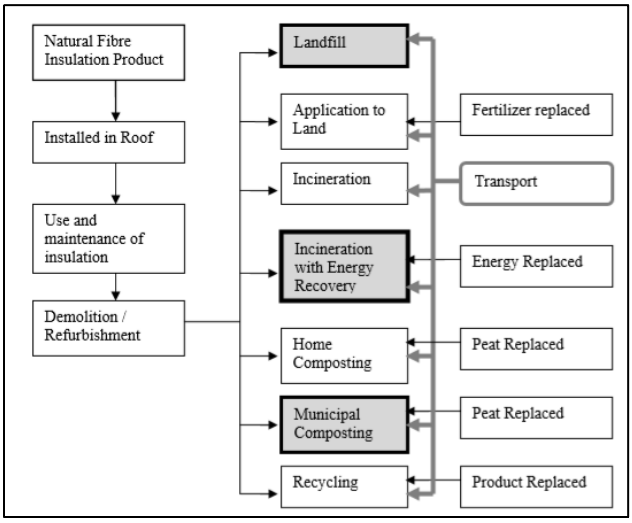


Figure 10: Potential end-of-life scenarios for natural fibre insulation (Norton, Murphy, Hill & Newman, 2009).

However, there is yet little data available or a detailed forecasting about the usable life for natural fibre insulation plates. Therefore, clear statements concerning recycling of insulation plates are difficult to give. Moreover, due to the additives as flame retardant and fungicide in bio-based plates, recycling is often difficult, and disposal of the plates normally takes the form of incineration with energy recovery. Incineration could be attractive due to the high content of the panels, but this requires special attention to the composition of the combustion gasses (Casas-Ledón et al., 2020). The combustion of the added chemicals and adhesives as flame retardant or fungicides could result in harmful pollutants within the combustion gasses. These concerns related with the end-of-life of insulation material limit a *cradle-to-cradle approach.*

The disposal phase could be a large contributor to carbon emissions in product footprinting, depending on the assumed end-of-life scenario (Casas-Ledón et al., 2020). For example, the research of Ardente et al. (2008) on kenaf fibre insulation included the disposal phase, assuming incineration. This represented 25% of the total carbon in the LCA, mainly due to the combustion of the polyester. The default scenario in 59.4 MJ_{prim} and 3.17 kg CO_2.eq/f.u., whereas two alternative scenarios resulted in lower values (Ardente et al., 2008). The first alternative scenario (incineration of the board) resulted in 41.0 MJ_{prim} and 1.93 kg CO_2.eq/f.u., and the second scenario (incineration of the board and the biomass residues) in 17.2 MJ_{prim} and 0.36 kg CO_2.eq/f.u. In particular, the energy recovery and the inclusion of the electricity production in the eco-profile could reduce the energy consumption of 30 ÷ 90%.

2.4 Economic viability of system changes

When implementing system changes in systems, economic viability is an important factor (Testa, Foderà, Di Trapani, Tudisca & Sgroi, 2016). To assess the economic viability of a project, a cost-benefit analysis can be performed. From an economic perspective, it is assumed that an activity is only undertaken if the total benefits exceed the costs. Often, there is a distinction between two types of costs, namely costs of investment (which are made initially) and operation and maintenance costs (which return every year). Costs of investment are among other costs of equipment and installation costs (Blok & Nieuwlaar, 2016).

2.4.1 Cost-benefit analysis: Net Present Value

A cost-benefit analysis is a method to analyse the economic-financial potential of a new project, crop or agricultural system (Testa et al., 2016). However, when in- and outflows of a project occur at different points in time, the simple cost-benefit analysis cannot be used without adjustments in the time component (Blok & Nieuwlaar, 2016). This is adjusted with the introduction of the discount rate in the formula of the Net Present Value (NPV). The discount rate is best explained in Blok & Nieuwlaar (2016): if someone does not care whether they receive €100 now or €108 a year from now, the time preference can be expressed by a discount rate of 8 percent. The NPV of a project can be described as the sum of the present values of yearly net cash flows during the project period and it takes into account the inflation and the returns of money relating to the present time and future (discount rate).

The formula of the NPV is as Equation 3 (Blok & Nieuwlaar, 2016):

Equation 3: Calculation of Net Present Value.

$$NPV = -I + \sum_{i=1}^{n} \frac{B - C}{(1+r)^i}$$

With

I = Initial investments
B = Annual benefits
C = Annual costs (excluding capital costs)
r = Discount rate
n = lifetime of the project

This formula considers that there is an initial investment, which is followed by a constant annual net benefit or cost. The use of the NPV-formula is widely used, and it can be said that the NPV is a proper approach to assess the viability of a project (Blok & Nieuwlaar, 2016). A project is attractive if the NPV-value is positive.

2.4.2 Carbon markets and carbon credits

In recent years, interest has grown in the potential to stimulate private investments with a carbon market to accelerate carbon reduction goals (Bonn et al. 2014). There is a distinction between the mandatory and voluntary carbon market (depicted in Figure 11), which principles are explained in the following paragraphs.

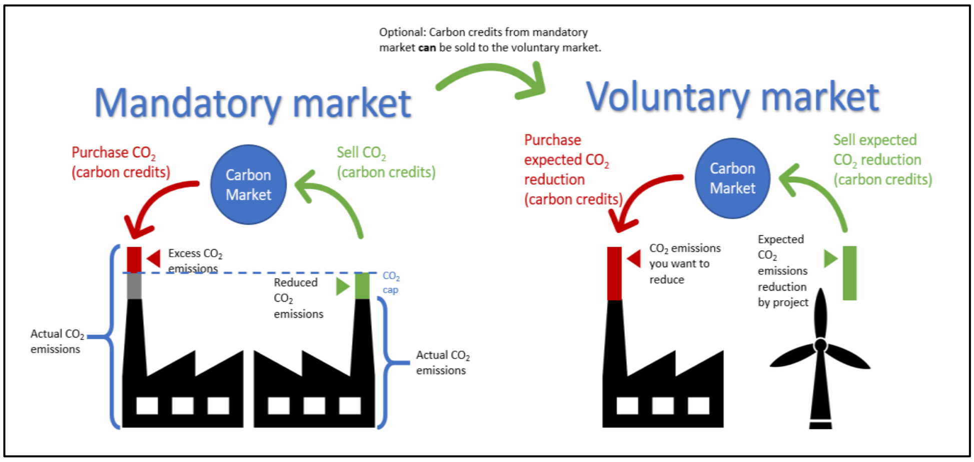


Figure 11: From mandatory to voluntary carbon market (Sustainalize, 2020).

Mandatory market

A so-called cap-and-trade system, based on allowances, implies that each participant (for example a country or region) is allocated a certain number of allowances based on an emissions reduction target. The finite supply creates a scarcity of allowances and drives the demand and prices. The EU's trading scheme is a good example to illustrate this market. In short, the Dutch government has set a reduction target and assigns a certain amount of GHGs to sectors (e.g. large industries), called emission rights. The sector should stay below this emission limit, or they can by carbon credits from business who stay below their emission gap. This is a so-called compliance market: the market is regulated by mandatory national, regional or international carbon reduction schemes (Van de Riet et al., 2014). The price for emission rights has drastically reduced over the last years due to the economic crisis, which has resulted in a surplus of the emission rights. The average price of an emission right has therefore fallen from €30 per t CO_2 in 2008 to €7 per t CO_2 in 2017 (Centraal Bureau Statistiek, n.d.), however prices are increasing again nowadays. Additionally, in the Dutch Climate Agreement adopted in 2018, a national CO_2-tax is introduced in 2021 to ensure that a 49% emission reduction in 2030 will be achieved compared to the levels of 1990 (Klimaatakkoord, 2018). For large industries, this implies that the CO_2-tax will start in 2021 at €30 per t CO_2 including ETS price.

Voluntary market

Another commodity is the baseline-and-credit system with carbon credits, which focus on the concept of additionality: a carbon offset buyer can only legitimately claim to offset his emissions if the emissions reductions come from a project that would not have happened anyway (Kollmuss, Zink & Polycarp, 2008). By specified activities in the LULUCF-sector (land use, land use change & forestry), emissions can be compensated and can optionally be included in the cap-and-trade system as the EU ETS (Van de Riet et al. 2014).

The voluntary market can enable companies or individuals to purchase carbon offsets on a voluntary basis when they would like to reduce their carbon footprint (Kollmuss et al., 2008). The global voluntary market has a significant smaller value compared to the compliance market but Bonn et al. (2014) state that the voluntary market can be more effective than the main market as it can provide direct finance to peatland projects. The emission provider allows a third party to verify the carbon emissions of a certain project (Van de Riet et al., 2014). According to Bonn et al. (2014), the market of voluntary carbon credit has been limited by low voluntary carbon prices, combined with high verification and accreditation costs. For example, prices of offsets from the Voluntary Carbon Standard, also known as Verra, vary at €5-15 per t CO_2, or between €10-20 at Gold Standard (Kollmuss et al., 2008). The Voluntary Carbon Standard and Gold Standard are two full-fledged carbon offsets certification standards which are recognised in accounting standards and verification.

2.5 Case study description: Paludiculture with cattail as bio-based insulator

Given the theory and concepts in the previous paragraphs, a case study of paludiculture with cattail as bio-based insulator is chosen. In this Section, the case study will be explained and existing literature regarding cattail properties and harvesting, commercial viability of paludiculture and previous research on carbon credits markets is summarised.

2.5.1 Restoration of peatlands: Paludiculture

Paludiculture is a way to rewet and therefore restore peatlands. Paludiculture combines wet agriculture on peatlands with the reduction of GHGs and continued land use with biomass production under wet conditions (Wichtmann & Joosten, 2007). It can take place at groundwater levels of 20 cm below to 20-30 cm above groundwater level, depending on the selected paludiculture crop (*paludicrops*). These crops are selected by the following criteria and are species that: (1) are able to grow under wet conditions, (2) produce biomass of sufficient quantity and quality and (3) contribute to peat formation (Wichtmann & Joosten, 2007). Paludicrops are for example cattail (bio construction material and insulation material), azolla (biodiesel), miscanthus (concrete, paper) hemp (textile, lime-hemp construction blocks) as well as fruits like berries (Van Duursen & Nieuwenhuijs, 2016).

2.5.2 Cattail properties and cultivation and harvesting processes

One of the potential paludicrops is cattail (*Typha spp*), which potential has been acknowledged in several literature studies and pilot projects (e.g. Geurts & Fritz, 2018). A pilot project from the Louis Bolk Institute revealed that out of the crop's cattail, willow, reed and miscanthus, cattail is the most suitable for wet cultivation and has good insulation properties (Bestman et al., 2019). Cattails are usually found in ponds, paddies, watercourses and lakes and are spread either by seeds which are transported by wind or water, or through roots. Van de Riet et al. (2014) conclude that cattail seems an excellent transition crop to go from dairy farming towards wet agriculture, as it has a high nutrient removal ability of phosphorus and nitrogen. Nutrients will be released into the water and cattail cultivation can be used to remove the nutrients by harvesting biomass (Van de Riet et al., 2014), as illustrated in Figure 12.

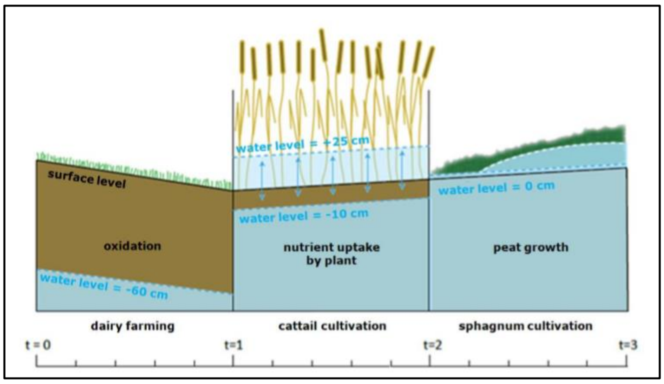


Figure 12: Transition from dairy farming to cattail cultivation in rewetted peatlands (Van de Riet et al. 2014)

There are several *Typpha* species among other broadleaf (*Typha latifolia*) and narrow-leaved cattail (*Typha Angustifolia*). Previous pilot projects use both species (Geurts & Fritz, 2018 and Figure 33 in Appendix 1).

Cultivation and harvesting of cattail biomass

Previous pilot projects have contributed to knowledge about the cultivation of cattail, as well as the changes necessary on the field to make the cultivation of cattail possible. Pilot projects are in different areas in the Netherlands and vary in experimental setting as species, soil removal, planting density and method. An overview of the current pilot projects in The Netherlands can be found in Appendix 1 (Geurts & Fritz, 2018). The largest cattail experiments take place Zegveld, Utrecht (4000 m^2). The knowledge about the cultivation and harvesting regime is fundamental for the proposed (LCA) in this research. Details on the cultivation and harvesting regimes are summarised in the following bullet points:

- **Ploughing and removing of topsoil.** Usually, ploughing and the removal of the topsoil are necessary to make the soil suitable for other management practices or crops. Nonetheless, when paludiculture is wanted, this is not necessary. Not ploughing results in a higher penetration resistance of the soil, which is beneficial for the machines at harvesting (Bestman et al., 2019). Additionally, not ploughing results in a higher yield as the intact soil has more nutrients, which increases the biomass/dry matter. Lastly, the plant litter is loosened during harrowing, which results in improved aeration (more O_2) and could therefore affect the methane emissions (Geurts & Fritz, 2019, p.50).

- **Fertilization.** Fertilization of the plants is necessary, with mainly nitrogen as the limiting factor of cattail growth (Pijlman et al., 2019).

- **Herbicides/pesticides.** When growing cattail at high water level, no herbicides/pesticides are needed as *Typha* has a high polyphenol content, which is beneficial against mildew and bacteria (Georgiev, Krus, Loretz & Theuerkorn, 2019). On top of this, an expert confirms this and explains that most weeds are suppressed with a high-water level and that pesticides are not desirable due to potential leaching (J. Pijlman, personal communication, March 9, 2020). The pilot project in Zegveld also shows this, as the pilot project started in 2015 with 66% of the surface covered with weeds, but this was decreased to 2% in late 2016 with no herbicides added (Bestman et al., 2019b).

- **Harvesting.** Several uncertainties remain about the time and frequency of harvesting. The time and frequency depend on the moisture content and related end-use of the material (Bestman et al., 201). Biomass of cattail can be used for several high-performance applications such as construction plate, roughage and insulation material (Van de Riet et al., 2014). When using as roughage, it is best to harvest before flowering obtain the highest feeding value and protein content, so during summer. However, to apply the crop as building material, it needs to be harvested as dry as possible. The crop is at its driest during winter or early spring. Harvesting can therefore be done once or twice a year, with an overall similar yearly yield (Bestman et al., 2019). Machines with (balloon) tyres are needed for harvesting cattail on wet fields which are adapted to saturated organic soils by having a low ground pressure (Figure 13) (Wichmann, 2017).

  Figure 13: Harvesting of cattail at Zegveld (Bestman et al., 2019).

  The biomass can be harvested in different ways: it can be collected in chaff, bundles or bales (Wichmann, 2017), the method depending on the end-use of the material and the crop. Research on the harvesting regimes in paludiculture areas has shown that to reduce the number of transport trips, bales are the most viable option (Schröder, Dahms, Paulitz, Wichtmann & Wichmann, 2015). The biomass is dried and compressed on the field, after which the bales are removed using a separate trailer. However, this can be unbeneficial for the ground pressure when harvesting machine goes over same place multiple time (Schröder et al., 2015).

2.5.3 Economic viability of paludiculture

The realisation of mitigation measures for peatlands often implies land use changes with important socioeconomic consequences (Wichmann, 2017). Economic aspects are important in changing current agricultural systems. In a previous study on the commercial viability of paludiculture, Wichmann (2017) states that land users only adopt sustainable practices if they are practical and financially viable. Additionally, Buschmann et al. (2020) state that land use alternatives are mainly determined by economic variables.
Previous studies on the implementation of paludiculture have been performed in Europe, although detailed information for The Netherlands is still lacking (Buschmann et al., 2020; Wichmann, 2018).

In the recent study of Buschmann et al. (2020), six European regions are compared regarding the socioeconomic and ecological business environments and related perspectives on agriculturally used drained peat soils. Whereas they do state that implementation of peatland protection measures as paludiculture largely depends on the local context and local actors, they mention some general conclusions which might be useful for the implementation of paludiculture on Dutch peatlands.

Overall, the system productivity, economic value of the land and market incentives are decisive. The farmers' willingness to change land use is low if the value of land is high as this could involve extensification of profitable land. The researched Dutch pilot project, Krimpenerwaard, has a relatively high average renting price, which limits the introduction of paludiculture. Implementation of potential alternative land uses is likely to be more adapted if there is a low agricultural profitability, or a more extensive land use. However, the monoculture of dairy farming on Dutch peatlands can be beneficial at implementing: Buschmann et al. (2020) state that conflict potential between different users is low. This is due to the land being used homogeneously and drainage can be installed and managed plot-specifically without affecting the (close) neighbouring fields.
Lastly, it is mentioned that institutional frameworks at different levels are necessary. EU-level incentives are necessary and implemented at regional institutions. The research showed that specifically for The Netherlands, the best incentive is said to be a policy instrument, funded by the provinces, in which farmers are incentivised to install drainage systems.

Another study by Hansson, Pedersen & Weisner (2012) was performed on the Swedish farmer's perception of the acceptance of climate smart agriculture on peatlands. It revealed that adequate subsidies, sufficient knowledge, peers' good experience and additional services could encourage landowners to construct wetlands. Barriers were deficient knowledge, burdensome management and time-consuming application procedures. They also see a potential role in subsidies to cover costs for individual farmers. However, they do state that when large-scale implementation is aimed, there should rather be focussed on the ecosystem services of peatland in general and valuing this, instead of only cover costs.

At last, another research from Geurts et al. (2019) also mentions the economic aspects of paludiculture as a barrier for large-scale implementation. Long-term schemes and income security are required. Potential subsidy schemes could be based on the acknowledgement of paludicrops as agricultural crop and thereby receiving agricultural payments from the EU Common Agricultural Policy (CAP). Other strategies can be the phasing out of the support of drainage-based peatland use (as dairy farming), subsidies for investments in paludiculture, or the *polluter pays principle*.

To conclude, previous research shows that different incentives might influence the succession rate of implementing different agricultural systems as paludiculture, which are mainly economic-oriented as this is one of the key incentives to adopt sustainable and alternative land use practices (Wichmann, 2017). One potential economic incentive could be the development of a carbon credit system, which concept is explained in Section 2.4.2. As stated by Bonn et al. (2014) it is likely that a combination of public and private investment is needed to conserve peatlands.

One example to highlight concerning successful development of a carbon markets and in combination with peatland restoration is MoorFutures (Günther, Böther, Couwenberg, Hüttel & Jurasinski, 2018). This voluntary carbon market is launched in 2011 and is the first carbon certificate to fund peatland rewetting. One MoorFutures certificate denotes one ton of CO_2.eq and are sold ex-ante to be able to cover the high initial costs (Günther et al., 2018). The price of one carbon credit can be calculated by dividing the total project costs divided by the ex-ante estimate of the emission reduction. To estimate these emission reductions, a baseline scenario ('with project') is compared to a reference scenario that would have occurred without implementation of the project. There should be said that reductions in N_2O emissions are not included. The price of MoorFutures is however rather expensive (€35 to €67 per t CO_2, depending on the project), which is mainly due to the development of an own standard to suit specific regional conditions, are therefore more cost efficient to implement.

Overview of the research questions and proposed methods

This paper is a thesis research project with two analyses, namely an environmental and economical analysis of the changing management practice from conventional dairy farming to paludiculture. The first analysis is done by performing an LCA (Section 3) and the latter one by a cost-benefit analysis (Section 4).

An overview of the input of the research and the proposed analyses is given in Figure 14.

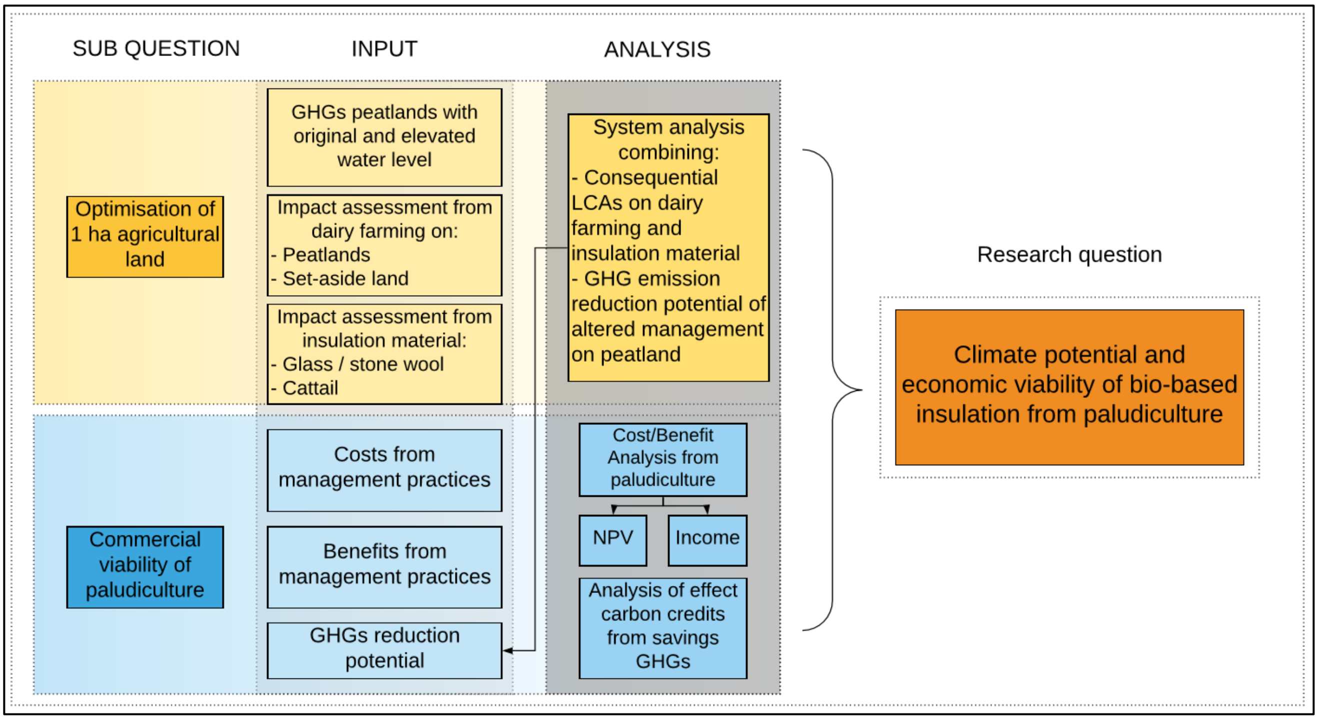


Figure 14: Overview of the research.

3. Methodology: Consequential One-factor Life-cycle Assessment

In this research, two systems are compared, which are depicted in Figure 15. In this assessment, the environmental impacts of two alternative ways of presently utilised peatlands are compared. In this research, three elements are investigated which are:

1) the substitution of fossil-based glass/stone wool by cattail insulation
2) the replacement of milk production from peatlands to set-aside land and
3) rewetting the peatlands (see Section 3.4)

In the first alternative, 1 ha peatland is used for dairy farming and a mixture of insulation wool (glass and stone wool, in equal share) is used as insulation material, produced from fossil resources. In the alternative system, 1 ha peatland is used as paludiculture area and the cultivation of cattail leads to the replacement of fossil-based mineral wool. The dairy farming is removed to set-aside land, which impact is neglected in the reference system. This comparison includes the elevation of the water level from dairy farming to paludiculture, referring to '*drainage*' and '*no drainage*' in Figure 15.

In the reference and the alternative system, the amount of land used and the produced goods are the same, thereby enabling a fair comparison between two systems. To conclude, the substitution method is used to see whether the sum of the three proposed elements in the alternative system provide a climate advantage compared to the reference situation. The focus of this research is set on the first element, substitution of insulation material. The milk production on either peatlands or set-aside land has not been investigated itself, but existing LCAs are used to give a system overview.

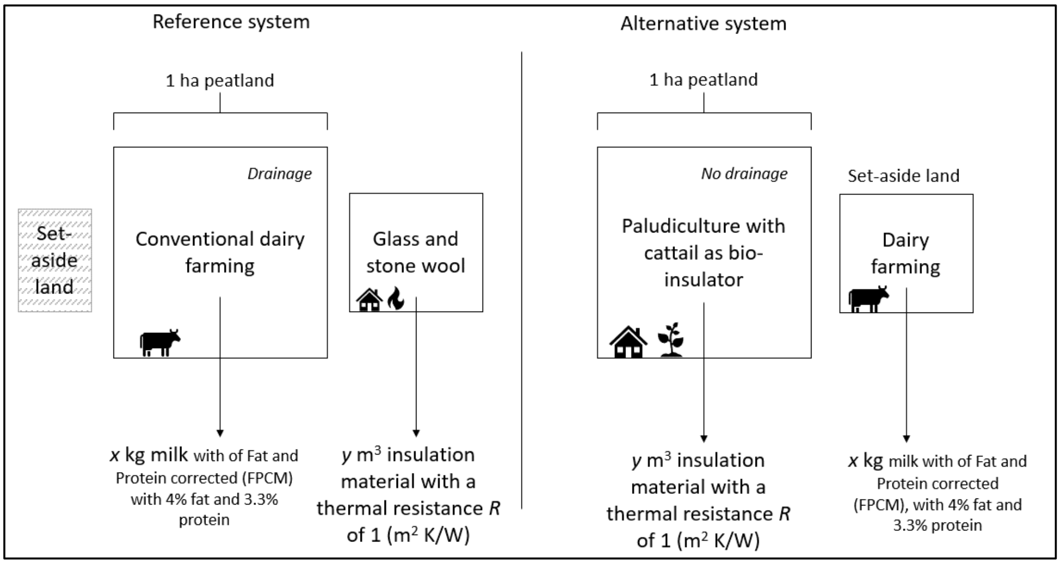


Figure 15: Schematic representation of the reference system (dairy farming) and alternative system (paludiculture).

The methodology of LCA is used to assess the impact of a product or process on the environment. This LCA consists of the following four categories:

- **Goal and scope definition** (Section 3.1)
- **Life-cycle Inventory analysis:** Dairy farming (Section 3.2.1) and insulation material (Section 3.2.2)
- **Life-cycle impact assessment** (Section 6.1)
- **Interpretation** (Section 6.4)

3.1 Goal and scope definition

Goal definition

The goal of this study is to compare the potential environmental impacts of two methods of utilizing presently used Dutch peatlands. The central goal of this study is therefore to assess the optimisation of 1 ha agricultural land from a climate perspective and giving an insight in innovation (paludiculture) in the agricultural sector.

This LCA is a consequential LCA (see Figure 7) as it aims to identify the changes that occur as a consequence of changing an agricultural system.

Scope definition

By means of system extension, the two systems are presented as two alternative ways to produce *x* kg of Fat and Protein Corrected Milk (FPCM) and *y* m^3 (or *z* kg) insulation material with a thermal resistance R of 1 (m^2 K/W). This provision of insulation and milk is the functional unit (f.u.) in this LCA. The exact magnitudes of *x and y* are intermediate results of the study. Both systems are determined with a limited focus on one impact category, namely climate change with the used proxy CO_2.eq. The used temporal scope for this impact is GWP-100.

Two types of allocation of emissions and resources are used: allocation to the coproducts of cattail and allocation in the combined milk and meat production at dairy farms. These allocation procedures are further elaborated in the separate sections on dairy farming and insulation material.

System boundaries

Dairy farming

The f.u.$_{milk}$ in the LCA of dairy farming is 1 kg of Fat and Protein corrected (FPCM) raw milk from dairy farms, with 4% fat and 3.3% protein. In both systems, the transport of the milk to the dairies (including on-farm milking and cooling), the use phase (the milk storage, preparation at home and waste) as well as the disposal phase is excluded from the research. Thus, the system boundaries are *cradle-to-farm gate.*

Reference system

Milk is produced on a dairy farm on 1 ha peatland. A summary of the flows and the related system boundaries is given in Figure 16 (left image). The category 'others' refers to the emissions at other raw materials as plastics and pesticides. The impact of the currently set-aside land is neglected. Thus, it is assumed that this land is not intensively used for food production and does not have a net GHG-emission.

Alternative system

In the alternative system, milk is produced on a dairy farm on 1 ha set-aside land. For simplicity, it is assumed that the milk production is replaced to any set-aside land in Western- or Central-Europe. An existing LCA of the Food and Agricultural Organization (2010) is consulted and a cradle-to-farm gate is assumed, as depicted in Figure 16 (bottom). The flows and the consulted LCA are further elaborated in 3.2 Inventory analysis.

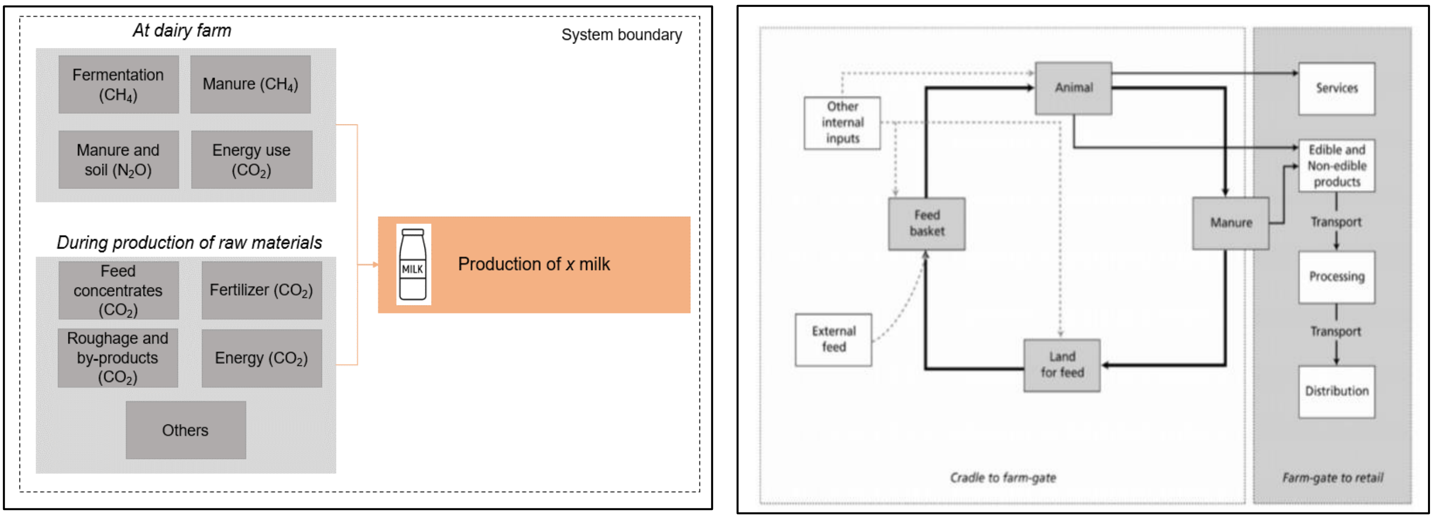


Figure 16: Flow chart and system boundaries of the LCAs of dairy production in the reference (left) and alternative system (right, from FAO, 2010).

Insulation material

According to Asdrubali et al. (2015), the evaluation of thermal insulation material is usually done by comparing the mass of material needed to obtain a thermal resistance (R) of 1 m^2 K/W. The mass (kg) of one plate is determined as the weight of an insulating board which involves a thermal resistance *R* of 1 (m^2 K/W) (see

Equation 2 in Section 2.3). This is from now on referred as $\text{f.u.}_{\text{insulation}}$. The system boundaries are *cradle-to-grave*. In both systems, the packaging of the material is included.

Reference system

Concerning the insulation material, a mixture of low-density glass and stone wool is assumed in equal share (50% stone wool, 50% rock wool). This mixture is chosen as it represents the most-used insulation material in Europe, with the market characterised by the domination of inorganic fibrous materials (glass and stone wool) for approximately 60% of the market (Karamanos et al., 2005). It is assumed that the Dutch insulation is also dominated by glass and stone wool. A summary of the flows and related system boundaries is given in Figure 17 (left).

Alternative system

Within the alternative system, cattail is used as a bio-insulator. Regarding the lifecycle of cattail and cattail insulation plates, the following steps are included and are depicted in Figure 17 (right).

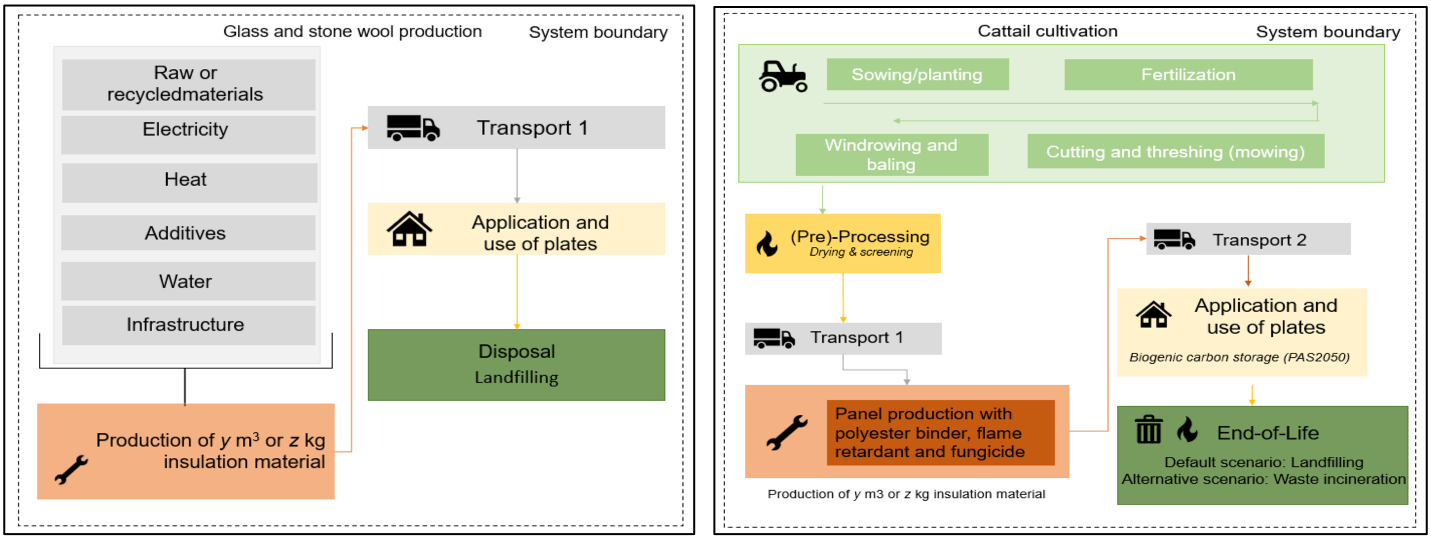


Figure 17: Flow chart and system boundaries of the LCAs of insulation material in the reference (left) and in the alternative system (right).

Some assumptions regarding the system boundaries are summarised in the following bullet points, where the *p* stands for production and the *a* for application:

- **Cultivation of cattail.** This category implies the following practices, namely fertilizer (p+a), rhizomes planting (a), cutting, mowing and combine harvesting, windrowing and baling. It is assumed that ploughing and harrowing do not take place at first start as it is not needed (Bestman et al., 2019; Geurts & Fritz, 2019, p. 50). The rhizome cultivation and transportation are excluded due to a lack of data, but the planting has been considered. Additionally, it is assumed that no herbicides/pesticides are used during plant growth, as previous pilot project revealed that the high water table and the high polyphenol content of cattail tackles weed formation (Georgiev et al., 2019; Bestman et al., 2019b). Lastly, the inundation of the area is excluded. Inundation of the area can be done by construction two small dikes, after the water level is raised by rain or ditch water with a pump. Currently, this water pump works on solar energy, but it should be noted that for larger areas, a diesel fuelled pump should be considered.
- **Production phase.** The raw material is pressed into bales and transported to the production plant, afterwards it is dried, cut, screened and cleaned and goes into the production phase**.** In this production phase, additives are added as a binder, fungicide and flame retardant.
- **Installation, maintenance and use.** The installation and maintenance impacts are neglected. It is assumed that installation is done by hand and no maintenance is required in the lifetime of the panel. In the LCA, the biogenic carbon storage is both excluded (following ISO-standards on biogenic storage) and included following the PAS2050-methdology.
- **End of life**. A default scenario is assumed with landfilling of the insulation plate. An alternative waste wood incineration scenario is proposed including the recovered energy/electricity, which is elaborated

in the Section 9: Sensitivity analysis. Following the waste hierarchy of the Waste Framework Directive, there is a preference of reusing and recycling elements before using them for recovery or dispose them. However, composting (recycling) of the cattail plates is not likely due to the support of polyester fibres. Moreover, due to the additives in the plates as flame retardant and fungicide, recycling seems a non-likely scenario.

3.2 Inventory analysis

This section is divided in the inventory analysis for dairy farming (Section 3.2.1) and insulation material (Section 3.2.2).

3.2.1 Dairy farming

It is decided to use existing data and impact assessments as representative data in both the reference as the alternative system because performing the LCA for dairy farming is not the main goal of this research.

Reference system

The most representative view of the carbon footprint of dairy farms in the reference system is based on detailed information about dairy farms which are located on peatlands only. This would be the ideal situation as this reflects the situation in the reference system at its best. Unfortunately, this detailed information is not (yet) available and therefore, general information about the carbon footprint of milk in The Netherlands is used as reference data. An elaborated LCA on *Sustainable Dairy Chain Farming* has been assessed by Doornewaard et al. (2017) as part of monitoring the progress of making the dairy chain more sustainable. Most Dutch dairy farms have a combined milk and meat production and in the consulted LCA, an average allocation of 85% milk to 15% meat is assumed over the period 2008-2017. All underlying assumptions of the LCA can be found in Doornewaard et al. (2017).

An overview of the consulted information and Inventory analysis can be found in Table 3.

Table 3: Dairy product carbon footprint details in the reference system (Doornewaard et al., 2017).

Category	Information	Inventory data
Product carbon footprint	The carbon footprint of milk is retrieved from Doornewaard et al. (2017). This includes the following categories: fermentation, manure, energy use, production of raw materials, concentrated food, roughage and by-products, fertilizer, energy during production of raw materials, other.	The average carbon footprint of the years 2011-2017 is calculated and assumed to be 1.232 kg CO_2.eq/f.u. In Figure 34 in Appendix 2, the detailed carbon footprint for each category is added. There should be said that the scatter of the carbon footprint is relatively big, which is added in Appendix 2 (Figure 35).

Alternative system

The milk production is replaced to set-aside land, but no exact area or country is assumed. It is assumed that the milk production is replaced to any set-aside land in Western-Europe. To reflect this situation, the milk production carbon footprint of Western-Europe is used, which is obtained from the Food and Agriculture Organization of the United Nations (FAO, 2010). An overview of the consulted information and Inventory analysis can be found in Table 4. More information about the consulted LCA can be found in Appendix 3.

Table 4: Dairy product carbon footprint details in the alternative system (FAO, 2010).

Category	Information	Inventory data
Product carbon footprint	The footprint is based on an average milk production of approximately 6000 kg milk cow^{-1} year^{-1}.	The carbon footprint of milk production (excluding deforestation) for Western-Europe is assumed to be 1.2 kg CO_2.eq/f.u. This value is derived from Figure 18.
Land use change	The feedstock for European cows is consisting of soybeans. The use of soybean is relatively high in the diet of European dairy cows. Most of the soybeans in Europe are imported from South America (FAO, 2010).	Average emissions attributed to land use conversion are estimated to be 0.09 kg CO_2.eq per kg FPCM for Western-Europe.

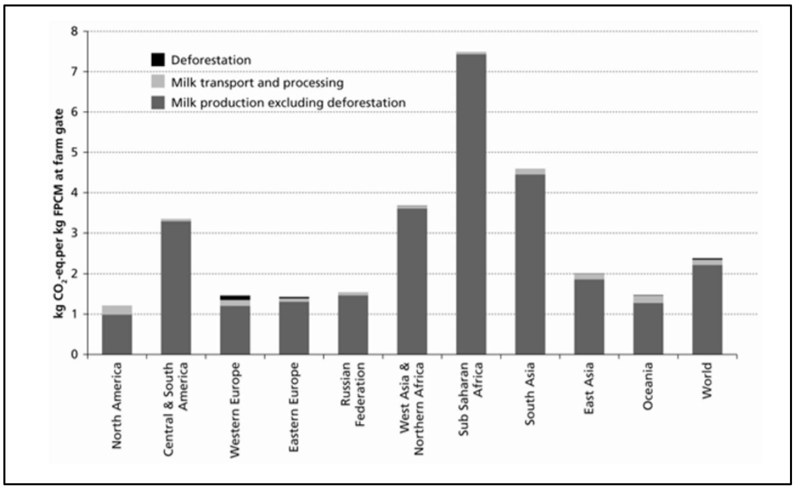


Figure 18: Estimated GHG emissions per kg of FPCM at farm gate, averaged by main regions in the world (FAO, 2010).

Western-Europe is considered as the largest producer of milk (roughly 24%), although this is related with a low relative contribution to world's GHGs of milk production, processing and transportation (15%) (Figure 36 in Appendix 3). By contrast, other areas (e.g. South Asia, Sub-Saharan Africa and Central and South America) are more emission intensive with relatively high emissions per kg of milk. The dairy farming sector of Western-Europe can be considered as efficient in terms of GHG emissions compared to other areas.

3.2.2 Insulation material

Reference system

A mixture of low-density glass and stone wool is assumed, in equal amounts. The EcoInvent database is consulted for reference flows of the carbon footprint of the insulation mixture. The assumed properties of the insulation plate are summarised in Table 5.

Table 5: Glass/stone wool properties from reference flow (EcoInvent).

GLASS/STONE WOOL PROPERTIES		GLASS WOOL	STONE WOOL
λ	W/m. K	0.040	0.037
ρ	kg/m^3	40	30

An average of the density of the reference flows for stone and glass wool is assumed, which gives an average of 35 kg m^{-3}. The average thermal conductivity is assumed to be 0.039 W/m. K.

The reference production flows for stone and glass wool are added in Appendix 4 (Figure 37 and Figure 38). Unfortunately, data from Dutch insulator producers was not available, therefore data from the *Rest of World* (RoW) data is used as reference flow. The used data is summarised in Table 6.

Table 6: Glass and stone wool carbon footprint details in the reference system.

CATEGORY	INFORMATION	INVENTORY DATA
Production of glass/stone wool mixture	The total carbon footprint of the glass/stone wool mixture is obtained from EcoInvent. An equal amount of 0.69 kg glass and stone wool is assumed. Both flows include melting, fibre forming & collecting, hardening & curing and internal processes. Additionally, energy carrier for furnace, packing and infrastructure are included	The carbon footprint is 3.44 kg CO_2.eq/f.u.$_{insulation}$ (*Rest of World*).
Transport 1	The insulation plates are sold at a hardware market. Transport of the plates is assumed to be road transport by large road lorry (loading capacity 26.2t). Transport of the plate to customer not considered.	It is assumed that the distance from the hypothetical factory to a hardware market is 85 km. This is based on the hypothesis that the factory is in the middle of The Netherlands. *Tonkm* is calculated with the weight of the produced insulation material (=*x*).

Disposal	Landfilling is assumed at the end-of-life.	The process *Waste mineral wool, for final disposal {Europe without Switzerland}| treatment of waste mineral wool, inert material landfill |* is used as reference flow, obtained from EcoInvent.

Overall, this gives a total of 3.44 kg CO_2.eq/f.u.$_{\text{insulation}}$ for the investigated system boundaries. A comparison of this reference value with literature is done in Section 9.2 (Discussion).

Alternative system

Within the alternative system, cattail is used as a bio-insulator. An annual average yield of 10 t DW ha^{-1} of broadleaf cattail is assumed. This considers that the first year's yield is relatively lower, but yield increases with an average of 10 t DW/ha over multiple years. This is based on pilot projects, with the longest pilot project with empirical data running for six consecutive years and expert expectations from interviews. J. Pijlman (personal communication, March 27, 2020) confirms that an average of 10 is a reasonable and T. Pelsma (personal communication, January 29, 2020) confirms with empirical data that over six consecutive years, the yield is within this range. Broadleaf cattail (*Typpha latifolia*) is chosen as this *Typpha* specie is mostly used in Dutch pilot projects (Appendix 1), especially at the pilot location Zegveld where a lot of knowledge for this research is obtained from existing literature.

Multi-functional processes

The harvesting of cattail delivers outputs, namely fibres and by-products, and additional field losses occur. There are yield field losses due to field practices as crumbling (processing by mowing) and harvesting of the crop (processing to bales). The percentage of loss is assumed to be approximately 5% based on average losses with grassland products (Wageningen Livestock Research, 2019). Additionally, at harvesting, by-products as manna grass, sparganium and yellowflag are assumed with a mass percentage of 10% (1 t), based by experiences from previous pilot projects (T. Pelsma, personal communication, January 29, 2020).

Additionally, when preparing the fibres, the fibres are screened and dried. It is assumed that 8% of the fibres is rejected, based on previous research from Bajwa, Sitz & Barnick (2015) on cattail composite boards and that there is 6% of dust in the dry mass of cattail (Grosshans, Dohan, Roy, Venema & McCandless, 2013). A schematic overview is given in Figure 19.

The substitution method (*system expansion*) is used to deal with the additional functions of the by-products and rejected fibres and using these as low-quality forage (discussed in sensitivity analysis, Section 6.1).

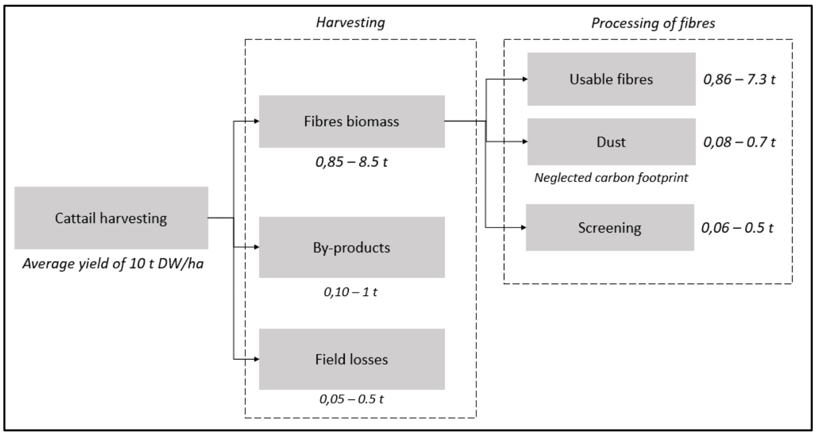


Figure 19: Main and by-products in the lifecycle of cattail.

Initially, all impacts are allocated to cattail production. The consumption of raw materials, diesel and electricity during the cultivation of cattail and refining the fibres is entirely allocated to the cattail and the production of residues from the rest products and non-usable fibres is neglected. These are assumed to be process wastes.

Description of the production process

The cattail board is an insulation board made by cattail fibres (82%) and polyester fibre (14%). This is chosen based on previous research with research about natural fibre insulation plates which are either hemp-based (Zampori et al. 2013) or kenaf-based (Ardente et al., 2008) considering roughly the same composition. Moreover, a binder, fungicide and a flame retardant are added which are needed in bio-based insulation material according to Uhlein et al. (2008). Background information regarding the production process and additives in bio-based insulation can be found in Section 2.3. The assumed properties of a cattail plate are summarised in Table 7.

Table 7: Specifications of a cattail insulation board.

CATTAIL INSULATION BOARD PROPERTIES	
	Percentage wt. %
Cattail fibres	82
Binder – polyester fibre	14
Fungicide – thiocarbamate	0.5
Flame retardant – borax	3.5

Additionally, specifications concerning the board density and thermal resistance of cattail is obtained. The thermal resistance of broad-leaved cattail is obtained from Duursen & Nieuwenhuijs (2016) and has the same ranges as traditional, fossil-based isolation materials as mineral wool (0.030-0.050 W/m. K) and EPS (0.032-0.040 W/m. K). The bulk density is assumed to be 50 kg/m^3, which is assumed to be a reasonable board density for natural fibre insulation (Casas-Lédon et al., 2020). Other research about natural fibres have same values as kenaf fibres (40 or 50 kg/m^3), hemp (50 kg/m^3) and cellulose fibres (50 or 60 kg m^3), also shown in Table 2. The assumed data for cattail insulation is summarised in Table 8.

Table 8: The kg needed to provide a thermal resistance of 1 m^2 K/W.

CATTAIL PROPERTIES		
λ	W/m. K	0.032
ρ	kg/m^3	50
A	m^2	1

According to Equation 2 (Section 2.3) and the considered thermo-physical properties showed in Table 8, the mass to obtain 1 m^2 K/W corresponds to an insulation board of 1.60 kg.

Data inventory

Data is mainly obtained through EcoInvent, reference values (CO_2-emission characterization factors) and previous research on fibre-based insulation material. Additionally, where empirical data was lacking, comparative research is used with representative crops/processes.

The assumed data is summarised in Table 9. Fuel is assumed to be diesel and the emission factor is retrieved from https://www.co2emissiefactoren.nl/ (CO_2 Emissiefactoren, 2019). The emission factor of natural gas is also retrieved from the same source.

Table 9: Data inventory for cattail insulation

Category	Information	Inventory data and reference flow
Crop rotation period	Assumed to be 30 years	More information in the alinea (*Biogenic and below-ground) carbon storage, delayed carbon emissions and lifetime* after this Table.
Germination and planting	Planting is done once in the lifetime of the cattail crop, by transportation with a tractor and planting by machine.	Data about the planting of miscanthus is used (roughly the same planting density per m^2 (2 and 0.5-2 for miscanthus and *Typha* respectively (Bestman et al., 2019)). Reference flow is the use of a tractor (35 kW) and a semi-automatic potato planter (4-row) (Peric, Komatina, Antoijevic & Branko, 2018).
Fertilization	Fertilization is done annually between harvesting of biomass and plant re-growth. The N, P and K loads are based on observed N:P and N:K ratios in growing *Typha* (Pijlman et al., 2019*)*. The ratio is	• Ammonium nitrate production and application of 200 kg NH_4-NC ha^{-1} yr^{-1} • Phosphorus production and application of 25 kg P_2O_5 ha^{-1} yr^{-1}

<table>
<tr><td></td><td>assumed to be 8:1:8 N:P:K. Nitrogen is added as ammonium nitrate, potassium is added as potassium nitrate (Geurts & Fritz, 2019, p.24) and phosphorus as P_2O_5.</td><td>• Potassium nitrate production and application of 200 kg KNO_3 ha^{-1} yr^{-1}</td></tr>
<tr><td>Harvesting: mowing and chopping</td><td>Harvesting is done annually in winter/early autumn when the crop is as dry as possible (Bestman et al., 2019). Harvesting is done by a single-axle tractor with twin tyres if necessary.</td><td>3.7 trips y^{-1} are needed for a field of 1 ha (Schröder et al., 2015). This is in the same order of magnitude with Peric et al. (2018), in which they assume six return loads for a yield of 24 t Miscanthus. Fuel consumption and performance time is obtained from Wichmann (2017):</td></tr>
<tr><td></td><td></td><td>
<table>
<tr><th>FUEL</th><th>UNIT</th><th>BALES</th><th>AVERAGE</th></tr>
<tr><td>Harvesting</td><td>l h-1</td><td>15-25</td><td>20</td></tr>
<tr><td>Transporting</td><td>l h-1</td><td>10-15</td><td>12</td></tr>
</table>
<table>
<tr><th colspan="5">PERFORMANCE TIME: H HA^{-1} OF HARVESTING OR TRANSPORTING</th></tr>
<tr><th>Total hours and litres of fuel needed/ha</th><th>hr ha^{-1}</th><th>Average</th><th>Total hrs for 3.7 trips</th><th>Liter ha^{-1} yr^{-1}</th></tr>
<tr><td>Harvesting</td><td>1-4</td><td>2</td><td>7.4</td><td>148</td></tr>
<tr><td>Transporting</td><td>1-4</td><td>2</td><td>7.4</td><td>88.8</td></tr>
</table>
</td></tr>
<tr><td>Windrowing</td><td>Windrowing is done annually with a tractor.</td><td>Data regarding fuel and tractor use is based hemp cultivation. It should be said that hemp has a higher yield (15 t DW ha^{-1}) (Zampori et al., 2013).</td></tr>
<tr><td>Baling</td><td>It is assumed that 49 bales are produced from 1 field of 1 ha (1 bale is 194 kg dry mass with a volume of 1.6 m^3, with a diameter of 1.30m and a width of 1.20 (Schröder et al. 2015)), thereby excluding field losses.</td><td>Reference flow in SimaPro with loading bales and baling (per piece), volume of bale is modelled as 1.4 m^3.

In the baling unit process, the amount of wrap film necessary is considered, which is high-density poly polyethylene.</td></tr>
<tr><td>Transport 1</td><td>Container transport with a tractor and a trailer is assumed. The transport from the baled cattail farm to the first processing plant is assumed to be 50 km. The loading capacity is max 26,2 t.</td><td><i>Tonkm</i> is calculated with the yield minus the field losses (9.5 t DW ha^{-1}) and the amount of km.</td></tr>
<tr><td>Drying of the biomass</td><td>The biomass is artificially dried. It is assumed that the moisture content is on average 70% at start and the final moisture content of the fibres is approximately 6%, determined as an appropriate value for insulation boards (Luamkanchanaphan, Chotikaprakhan & Jarusombati (2012).</td><td>No data could be found about the drying process of cattail. Data on the industrial drying of forage is used, which has on average a similar moisture content input (74.2%) and moisture content output (average: 8.2%). The average energy use per ton dehydrated forage is used (Van Zeist et al., 2012). It is assumed that the energy is generated by natural gas. The carbon footprint of natural gas is calculated with the higher calorific value of standardised Dutch Groninger gas (35,095 MJ/m^3).</td></tr>
<tr><td>Panel production</td><td>The transportation of the additives is excluded.</td><td>Carbon footprints of the polyester fibre (polyester-completed starch binder), PE film (Packaging film, low density, PE), binder, fungicide and flame retardant are retrieved from the EcoInvent but for the cattail production, no literature data nor database information is available.
Data for the production of a kenaf fibre panel is used from an Italian company, which has been used in a preliminary LCA of hemp-based insulation as well (Zampori et al., 2013). It should however be noted that this plate had 15 wt. % of polyester fibre, but this data is used as no other literature is available. This data includes the following phases: fibre preparation, carding, thermal biding, cutting of the panel and packaging (Zampori et al., 2013).</td></tr>
</table>

		• To produce the panel, the preparation and mixing: 0.0022 kWh/kg_{fiber} and 0.001 l H_2O/kg_{fiber}. • Actual panel production: 0.16 kWh/kg_{panel}, 2.043 MJ/kg_{panel} and 0.0012 g of PE film/kg_{panel} The carbon footprint of 1 kWh is retrieved from Centraal Bureau voor de Statistiek (2018), based on the integral method.
Transport 2	The insulation plates are sold at a hardware market. Transport of the plates is assumed to be road transport by large road lorry (loading capacity 26.2t). Transport of the plate to customer not is not considered	It is assumed that the distance from the hypothetical factory to a hardware market is 85 km. This is based on the hypothesis that the factory is in the middle of the country and the furthest distance within the country is 85 km. *Tonkm* is calculated with the weight of the produced panels and the amount of km.
End-of-Life	In the default scenario, landfilling is assumed.	It is assumed that the insulation plates are landfilled in an airtight environment, which results in no net CO_2-emissions during the disposal phase.
	In the alternative scenario, the plates are treated as waste wood and incinerated. This can generate some heat. This scenario is analysed in the sensitivity analysis (Section 9.1).	

(Biogenic and below-ground) carbon storage, delayed carbon emissions and lifetime

A problem in present LCA methodology is that past, present and future emissions are treated equally and integrated over time, and it is often assumed that the biological uptake during growth and release in the end-of-life phase are assumed to simply cancel each other out (Wijnants et al., 2019). However, the biogenic carbon storage in bio-based products could lead to positive long-term effects when the carbon is stored in the anthroposphere before released again in the atmosphere after a long-time span (Garcia & Freire, 2014).

The following assumptions are done regarding the biogenic carbon uptake and below-ground biomass.

- **Biogenic carbon uptake**: An average carbon content in cattail of 41.2% is assumed (Grosshans et al. 2013). Biogenic storage is (not) dealt with in two ways: A standard LCA is performed, thereby excluding biogenic storage (following ISO-standards), but biogenic carbon uptake is also considered (following the PAS2050-methodology). The delayed released method of the PAS2050 (Section 2.2.2) is followed and it is assumed that the emissions are delayed for more than 25 years from the formation of the product. The use phase of the cattail plates is assumed to be 50 years, roughly equal to the lifetime of a house. The chosen time-horizon for the assessment of the insulation plate carbon footprint is 100 years, which is the most common time horizon used in LCA and carbon footprints (Garcia & Freire, 2014).
  Following from Equation 1, this results in a weight factor of 0.5 for the delayed impact of biogenic CO_2 emitted at end-of-life. The weighting factors are multiplied by the total biogenic CO_2 emissions arising at the end-of-life of the plate, after which the impact of these emissions reflecting the timing of release is obtained.

- **Carbon uptake in below-ground biomass:** It is assumed that below-ground biomass maintains in a steady state for much of the crop's lifetime. Heller, Keoleian & Volk (2013) calculated the carbon sequestration of the perennial crop willow and concluded an average of 2.0 t CO_2.eq ha^{-1} yr^{-1} with a similar shoot-root ratio compared to cattail. The shoot-root ratio of both cattail and willow is 1.75, based on the soil regime of continuous flooding (Li, Pezeshki & Goodwin, 2004). Besides, in the Green Deal Pilot Nationale Koolstofmarkt (2018) on rewetting projects, Geurts & Fritz state that a one-time average of 20 t CO_2.-eq ha^{-1} is stored in cattail underground compared to conventional grass.

  The carbon uptake is recalculated according to the crop rotation period and project lifetime. In previous research on bio-energy crops (e.g. Van der Hilst et al., 2010; Smeets, Lewandowski & Faaij, 2009), the project lifetime is equal to the lifetime of the researched crop. Nevertheless, there are large uncertainties in the cattail lifecycle due to a lack of empirical data (J. Pijlman, personal communication, February 5, 2020). However, Van de Riet et al. (2014) state that rewetting project are expected to run for 30-50 years, which assumes that the below-ground carbon is stored for a longer period. A lifetime of 30 years is chosen for the stored carbon as this is deemed to give a more representable view over the expected lifecycle.

An average of these two values, namely 2.0 t CO_2.eq ha^{-1} yr^{-1} and 20 (considered over 30 years) is assumed.

3.3 Impact assessment: Carbon Footprint

Global Warming Potentials (GWPs) are proposed to describe the extent of warming capacity relative to the capacity of CO_2. The carbon footprint can be calculated with Equation 4.

Equation 4: Carbon footprint calculation

$$Carbon\ footprint = \sum_i GWP_i \times M_i$$

Where *M* is the mass (in kg or t) of an emission gas *i, GWP_i* is the global warming potential of the *i*th emission gas. The GWP characterization factors with a lifetime of 100 years are assumed. However, there should be mentioned that characterization values are not consistent in the used datasets and studies of this research. The ideal approach is to correct the calculations with one consistent approach, but this was not possible in this research as the calculations of the used datasets and studies are not publicly published and therefore not reproducible. Although the characterization factors differ, it is still decided to compare the proposed data and solutions as the values differ roughly less than 10%. In Table 10 the characterizations factors are mentioned, with the standardization of CO_2 to 1.

Table 10: Characterization values used in impact assessment.

Category	Characterization factors	Reference year
LCA: - **Cattail** - **Glass/stone wool** - **Dairy farming alternative system**	CH_4: 28 N_2O: 265	IPCC 2013 GWP100a
LCA: - **Dairy farming reference system**	CH_4: 25 N_2O: 298	IPCC 2007
GHGs peatlands	CH_4: 28 N_2O: 265	IPCC 2013 – without feedbacks

3.4 Change in GHGs emissions of peatlands due to elevated water table

The greenhouse gas emissions of peatlands are divided in CO_2, N_20 and CH_4 emissions and their contribution is being taken account with the relative GWP characterization factors. In this thesis, a model about the GHGs and related water levels is used, which is a combination of the methods and data proposed in Fritz et al. (2017) and Jurasinski et al. (2016). The model and data is checked with an expert (M. Hefting, personal communication, February 14, 2020) and it can be used as a basic model, but it does have limitations, which will be mentioned in Section 9.3.

1. Determination of the emissions of the baseline

The baseline of the GHGs emissions from peatlands is related to the average groundwater level. An emission reduction of -4.5 t CO_2 ha^{-1} yr^{-1} per 10 cm groundwater lowering is assumed (Figure 20), which is in line with data for Europe (4.9 t CO_2 ha^{-1} yr^{-1} per 10 cm) (Fritz et al., 2017). The circles are related to direct measurements, triangles are indirect measurements related to land subsidence. The emissions in Figure 20 are for extensively used peat areas and emissions are therefore calculated conservatively. It is expected that with more intensive use the emissions will increase (Fritz et al., 2017). Measuring CO_2 and CO_2.eq fluxes is relatively difficult, CO_2-fluxes are currently measured through chamber measurements, and this method is quite sensitive. When the soil starts to shake even a little, this can lead to methane bubbles, of which it is unknown how long they have been there and whether it is representative for CO_2-fluxes (M. Hefting, personal communication, February 14, 2020). Overestimation is countered with this conservative approach.

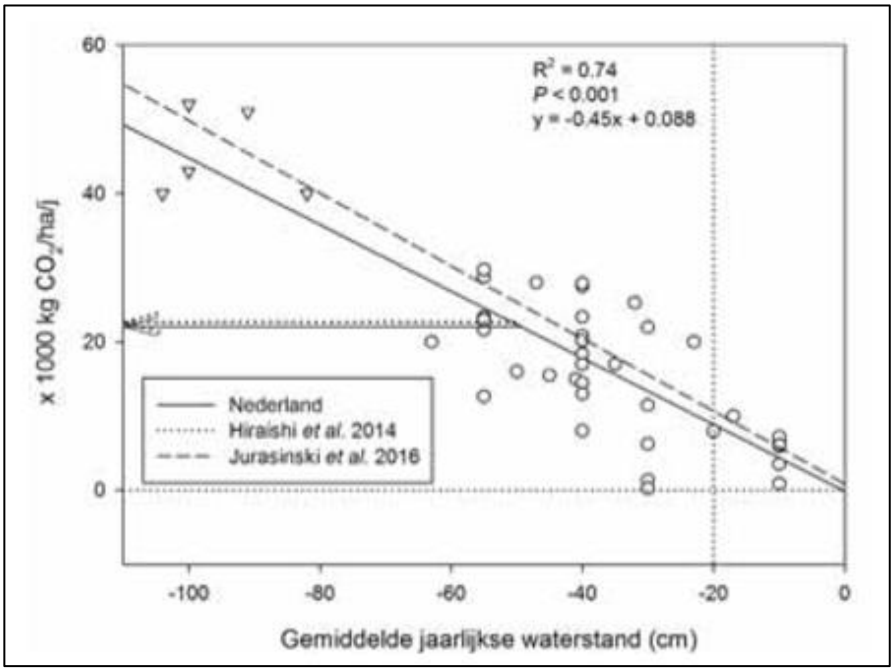


Figure 20: CO_2-emissions and land subsidence in Dutch peat meadows areas in relation to the groundwater level (Fritz et al., 2017).

Where necessary, adjustments are made for the CO_2.eq emissions of CH_4 and N_2O in relation to the groundwater level. The proposed model is added in Table 11. These emissions are derived from Jurasinski et al. (2016).

Table 11: Proposed model of GHG emissions from peatlands related to the groundwater level (Fritz et al., 2017; Jurasinski et al., 2016).

Average groundwater level (cm)		**CH_4 and N_2O-emissions**	**CO_2-emissions**	**Total $CO_{2.eq}$ emissions**
		t CO_2.eq ha^{-1} yr^{-1}	*t CO_2 ha^{-1} yr^{-1}*	*t CO_2.eq ha^{-1} yr^{-1}*
+50				14,9
+40				14,6
+30				14,3
+20	*Assumed water level*			13,5
+10				10,8
0		8,9	0,1	9,0
-10		4	4,6	8,6
-20		1,9	9,1	11,0
-30		2,6	13,6	16,2
-40		4,4	18,1	22,5
-50		1,8	22,6	24,4
-60		0,2	27,1	27,3
-70		0	31,6	31,6
-80		0	36,1	36,1
-90		0	40,6	40,6
-100		0	45,1	45,1

An average groundwater level of -10 cm is optimal in terms of total CO_2.eq emissions. However, the optimal water level for cattail are higher, between 20 to 30 cm above the soil surface (Pijlman et al., 2019; Wichtmann & Joosten, 2007). Yet, continuously keeping this water level is difficult throughout the year, as these water levels are relatively high compared to the groundwater level. The field should be permanently rewetted, but this is sometimes hard to achieve, especially in dry summer times (M. Hefting, personal communication, February 14, 2020). Therefore, it is decided that the water level of the optimal growing conditions of cattail are too optimistic to achieve for the whole year. A more realistic water level of 0 to + 20 cm is assumed. This is a lower range than the optimal water level for cattail, but in this way, it is tried to account for fluctuations in the water table throughout the year. An average CO_2.eq at a water level of 0 to + 20 cm above groundwater level is assumed to be 11.1 t CO_2.eq ha^{-1}, which is the average of the CO_2.eq emissions at 0, +10 and +20 cm.

2. Determination of the emission reduction potential

After determining the baseline, the emission reduction potential is calculated, which is the difference between the emissions before the increase in the water level and the emissions after an increase. In this research, there are three drainage categories which are assessed:

- Rewetting scenario 1 (AS1): from **-90 to -100 cm** towards 0 up to +20 cm (cattail-based paludiculture)
- Rewetting scenario 2 (AS2): from **-60 to -90 cm** towards 0 up to +20 cm (cattail-based paludiculture)
- Rewetting scenario 3 (AS3): from **30-60 cm** towards 0 up to +20 cm (cattail-based paludiculture)

Additionally, an uncertainty adjustment is added. This is done as there are potential risks of extra CO_2 leaching from peatlands due to e.g. mowing and cracking of the soil. For example, cracking of the soil in drier periods can result in O_2 leaching into the (deeper) soil and can affect the oxidation reaction rate, thereby influencing the CH_4 emissions from the peatlands (Brouns, 2016). Moreover, when cattail is mowed, small air vents can arise in the peat soil which can serve as chimneys in which O_2 can penetrate (M. Hefting, personal communication, February 14, 2020). For now, a risk adjustment of 10% is assumed. The emission reduction potential can be calculated with Equation 5.

Equation 5: Emission reduction potential.

$$Reduction\ potential = (CO_2.eq_{o,wl\ t} - CO_2.eq_{e,wl\ t}) - uncertainty\ adjustment\ (10\%)$$

With o,wl = original water level
e,wl = elevated water level

4. Methodology: Commercial viability of paludiculture

4.1 Overview

The economic viability is an important factor for system changes in (agricultural) systems. The viability is assessed by performing a cost-benefit analysis, following the methodology as proposed in Section 2.4.1.
Two scenarios are assumed:

- Default scenario: Without carbon credit system (Section 4.3)
- Alternative scenario: With carbon credit system (Section 4.4)

4.2 Data inventory

Dairy farming

Due to time limitations and the aim to focus in this research on paludiculture, it is decided to use existing data on the economic performance of dairy farming as a reference. The most detailed reference is the research performed by the Wageningen Economic Research Group (formerly known as Landbouw Economisch Instituut) (Vogelzang & Blokland, 2011). This data is used in another research about the viability of paludiculture as well (Van de Riet et al., 2014). The reference scenario is a dairy farm with Holstein-Frisian cows, which has a revenue of approximately 33 euro per 100 kg milk in the period 2001-2009. Currently, the price of milk is increased to approximately 36 euro per 100 kg milk (Eurostat, 2020, last update April 7th). Therefore, the outcomes of the performed research could be an underestimation of the current situation but are to a large extent representable. It should be said that the assumed milk production per cow is lower at the reference farm, with 7732 kg milk cow^{-1} y^{-1} and 8960 kg milk cow^{-1} y^{-1} assumed in the LCA.

A summary of the assumed revenues and costs is given in Table 12. The detailed and thereby complete costs are added in Appendix 5 (Table 29).

Table 12: Summary of the average income per cow and per 100 kg milk at a Dutch dairy farm in the period 2001-2009 (Vogelzang & Blokland, 2011).

CATEGORY	EURO PER 100 KG MILK
Revenues	42.35
Costs	12.09
Non-allocated costs	21.91
Total	8.35

Paludiculture

Cost and revenues of crop production are highly regionally specific. The variables depend on e.g. the farm management, soil and climate and the economic environment (Van der Hilst et al., 2012). Therefore, only an estimation can be given based on best-available data. Calculations are carried for the current year (2020) using data from literature. An overview of the costs is given in Figure 21.

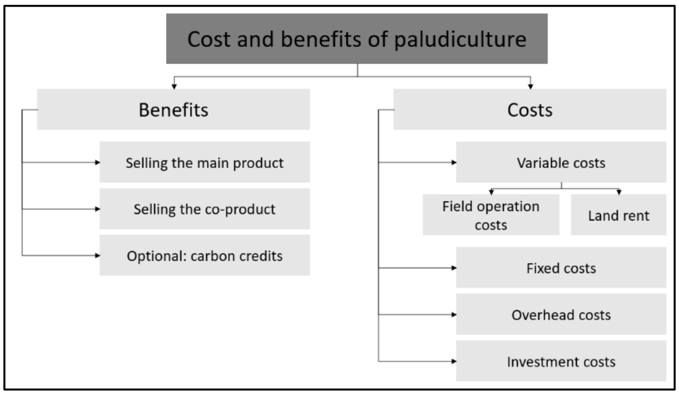


Figure 21: Overview of the costs and benefits of paludiculture.

Benefits

The considered benefits from cattail-based insulation are summarised in Table 13.

Table 13: Benefits from paludiculture.

CATEGORY	INFORMATION
Selling the cattail fibres	Duursen & Nieuwenhuijs (2016) state that an average price of €100-200 per t DW is plausible for raw material. Van de Riet et al. (2014) state that a revenue of €300-500 per t DW is possible after the fibres are processed, with a total revenue of approximately €4800 ha^{-1} . In this assessment, the separated fibres are sold, which have an average price of €400 per t DW. It is assumed that the revenue linearly increases from year 2 and is at the maximum revenue is achieved at year 5. This is based on the experience from the longest Dutch pilot project running, which is currently six years.
Selling the by-product and rejected fibres	It is assumed that the by-products (potentially be used as low-quality forage) do not have an (significant high) economic value.
Optional: Carbon credits	The introduction of carbon credits, resulting from rewetting the peatland and changing the agricultural purpose an area, could be an extra revenue. This is further explained in Section 4.4

Costs

The costs imply a large and diverse number of categories, which need to be executed annually or once. The costs are divided in in variable, fixed, overhead and investment costs. The overhead costs, which imply maintenance for the barns and farm, cleaning and administration are excluded due to a lack of data.

Variable costs

- **Land rent**: Two main areas have a large share of peatlands (North-Netherlands and West-Netherlands), therefore it is decided to have two variable land costs. The lease price of the land is used to reflect the land costs for farmers. Lease prices are based on the Pachtnormen Besluit 2019 (Rijksoverheid, 2019) and given in Table 14 .

- **Field operation costs:** imply the following categories in Table 14. The used data is summarised in Table 15.

Table 14: Considered categories in variable and field operation costs.

COST CATEGORY	CATEGORY	SOURCES AND INFORMATION
Land rent	Land lease price	North-Netherlands (area 'Noordelijk weidegebied'): €646 ha^{-1} West-Netherlands (area 'Hollands/Utrechts weidegebied'): €796 ha^{-1}
Field operation costs	Diesel costs	Diesel costs are assumed to be €1.24 per litre (diesel price April 13th, 2020)
	Rhizome planting	The rhizome planting is done with a diesel tractor (35 kw) and a semi-automatic potato planter (4-row).
	Fertilizing	The diesel consumption has been obtained from the unit process 'Fertilizing' in SimaPro, afterwards it is recalculated to the number of litres considering the average density of diesel 0.832 kg L^{-1}. The price for fertilizers is retrieved from De Wolf & Van der Klooster (2006). The total fertilizer costs are €85 ha^{-1}, which is in line with empirical data from the cultivation of miscanthus[1]. No pesticides are used.
	Harvesting	The fuel consumption rate and performance time are retrieved from Wichmann (2017), combined with the number of trips necessary, based on Schröder et al. (2015).
	Windrowing	Windrowing is done with a diesel tractor and performance time is obtained from Zampori et al. (2013).
	Baling	Diesel consumption is obtained from the unit process 'Baling' in SimaPro, afterwards it is recalculated to the number of bales considered in the research. However, data on the performance time was missing, therefore Zampori et al. (2013) was consulted for performance hours. It is checked if the diesel consumption in Zampori et al. (2013) is in the same order of magnitude, which is the case (37.95 l ha^{-1} compared to 45.6 l for all bales in SimaPro). For the wrapping film (HDPE), an average price of €1350 per t is assumed based on the price level in 2016 (Van den Oever, Molenveld, Van der Zee & Bos, 2017).
	Transportation	It is assumed that the harvested biomass needs to be transported across 135 km in total. Return trips of the trips are also added, although with no return loads. The diesel use depends on the mass of the transported biomass (empty: 0.2 l km^{-1} and full: 0.4 l km^{-1}). Total transportation costs imply fixed costs, labour costs, diesel costs and other

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[1] Confidential data, January 24, 2020.

	variable costs. Data is obtained from Smeets et al. (2009), based on truck transportation with a maximum of 27 t. Data for unloading the biomass implies labour hours, diesel costs and capital and operation and maintenance costs.
Labour costs	Labour costs are calculated by multiplying labour price by 1.1 to account for unproductive time required for travelling, servicing and lubricating (Smeets et al. 2009). This is multiplied with the performance times. The labour price is assumed to be €30 ha^{-1}, so the labour costs are €33 ha^{-1}.

Table 15: Data used for the different categories in field operation costs.

	PERFORMANCE TIME (H HA^{-1})	DIESEL CONSUMPTION (L HA^{-1})	OTHER DATA
Rhizome planting	3.33	28.0	
Fertilizing	1.6	6.3	The price for the fertilizers: €20/100 kg for N, P and K (De Wolf & Van der Klooster, 2006).
Harvesting & transporting	Harvesting: 7.4 Transporting: 7.4	Harvesting: 148 Transporting: 88.8	
Windrowing	4	23.6	
Baling	3	45.6	The price for the wrapping film: €1350 t^{-1} HDPE-film (Van den Oever et al., 2017), resulting in €68.85 for the wrapping film.
Transportation	Transportation: 0.8 (Un)loading: 2.4	Transportation: 81 (Un)loading: 21	
Labour hours	Sum of all performance times (including transport): 30		The price of one labour hour is €33 h^{-1}.

- **Fixed costs:** In literature, there is a lack of empirical data about the fixed costs as depreciation of land, buildings and investment for new machines. This is therefore, unfortunately, left out of the analysis. The fixed machinery costs have been considered with data from the research from Wichmann (2017), specifically for machinery for paludiculture areas. This article concluded that, although the range is relatively wide due to the different working conditions of the interviewees, the fixed machinery costs varies between €-287 to €677 ha^{-1} y^{-1}. The mean was €115 ha^{-1} y^{-1}, however with a large standard deviation of €127 ha^{-1} y^{-1}. This wide range of values (operating time per year, acreage performance, harvester purchase costs) reflects the wide variety of machines and site conditions.

- **Investment costs:** Additionally, according to Van de Riet et al. (2014), a one-time investment of €7300 ha^{-1} is necessary for the transition to cattail cultivation. This includes costs for dams and pumps and is based on the experience of setting up a 10 ha cultivation site in Ilperveld, North-Holland. R. Westerhof (personal communication, March 19, 2020) also confirms that an indicative investment of €6000 to €8000 per hectare is necessary for paludiculture. Approximately 10.000 plants ha^{-1} are needed with an average price of ~0.30 €/ha (Duursen & Nieuwenhuijs, 2016).

4.3 Default scenario: Economic viability without carbon credit system

Paludiculture

At first, it is assumed that there are no carbon credits introduced, thus the revenues are limited to the main product. The costs and benefits during the lifecycle are discounted by calculating the Net Present Value (NPV), derived from Equation 3[2].

Discount rate

The discount rate is assumed to be 6%. Discount rates vary in literature about biomass crop production, but values in the same order of magnitude have been done in previous literature and is assumed to be a realistic rate

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[2] Equation 4: NPV-value (Blok & Nieuwlaar, 2016):

$$NPV = -I + \sum_{i=1}^{n} \frac{B-C}{(1+r)^i}$$

for farmer loans (5.5% in Van der Hilst et al., 2010; 7% in Faaij, Smeets, Stampfl & Lewandowski, 2007). The effect of the discount rate is analysed in Section 9.1 (Sensitivity analysis).

Annuity period

The annuity time considered is 30 years, equal to the lifetime of the crop, but this choice is arbitrary. The development of cattail after six years is not known. It is for example not known if new rhizomes are needed within this circle of 30 years, which comes with additional costs for rhizomes and planting. Nonetheless, for rewetting projects, a lifetime of 30-50 years is also realistic (Van de Riet et al. 2014). Additionally, the verification of (voluntary) carbon credits also implies a long-term carbon reduction as a prerequisite, with forestry projects from Verra running for example 30-40 years.

The occurrence of the different cost categories within this period is summarised in Table 16. For the years 2-4, it is assumed that 50% of the total costs for harvesting, windrowing, transportation and related labour costs apply because of the lower assumed yield in these years. This results in less field operation costs.

Table 16: Occurrence of cost categories in lifetime of cattail.

	YEAR 1	YEAR 2	YEAR 3	YEAR 4	YEAR 5-30
Land rent	X	X	X	X	X
Rhizome planting	X				
Fertilizing	X	X	X	X	X
Harvesting		X	X	X	X
Windrowing		X	X	X	X
Baling		X	X	X	X
Transportation		X	X	X	X
Labour costs	Rhizome planting, fertilizing	X *excluding rhizome planting*	X *excluding rhizome planting*	X *excluding rhizome planting*	X *excluding rhizome planting*

4.4 Alternative scenario: Economic viability with a carbon credit system

A carbon credit market can stimulate private investments for peatlands restoration (Bonn et al., 2014). In the alternative scenario, it is tried to assess if the introduction of a carbon credits could affect the economic viability of paludiculture. To be clear: these carbon credits are only attributed to the GHG reduction potential of peatlands related to the higher water level.

Two market are investigated, namely the compliance market (focused on the baseline-and-credit system) and the voluntary market (focused on additionality). The used carbon offset prices for each offset are summarised in Table 17.

Table 17: Carbon prices at compliance and voluntary market.

CARBON COMMODITY	PRICE (€ T^{-1} CO_2)	CARBON MARKET	SOURCE
Compliance market: Baseline-and-credit system	7	Current price in EU ETS trading scheme	Centraal Bureau voor de Statistiek (n.d.)
Voluntary market	10-20	Gold Standard	Kollmuss et al. (2008)
	35-67	MoorFutures	Günther et al. (2018)

It is assumed that the project lasts for 30 years. The following steps are proposed:

1. **Calculation of the emission reduction potential of a higher water level over a period of 30 years.** This step implies the reduction potential of the higher water level from dairy farming to cattail insulation production. To calculate the total emission reduction potential over 30 years (*n*), Equation 6 can be used.

Equation 6: Total emission reduction potential over 30 years.

$$\sum_{n=30}^{n} CO_2.eq_{saved}\ (t) = \sum (CO_2.eq_{saved_{yearly}} \times n)$$

2. **Calculation of the carbon credits.**
   The savings from offsetting the carbon emissions are calculated with Equation 7.

   Equation 7: Calculation of extra revenues from carbon credits.

$$Revenues_{carbon\ commodity}\ (€) = \ CO_2.eq_{saved}(t) \times price\ carbon\ credit\ (€\ t^{-1}\ CO_2.eq_{saved})$$

   The carbon prices from the compliance and voluntary market are analysed, thereby using the different prices in Table 17.

3. **Introduce the additional revenues of carbon credits in the baseline scenario.**
   At the final step, the additional revenues are included in the default scenario (without carbon credits). The effect of the carbon credit market is analysed by comparing the yearly income and NPV of the default and the alternative scenario.

4. **Calculating the carbon breakeven price 1) when the NPV is ≥ 0 and 2) income of paludiculture could compete with dairy farming**
   It might turn out that the income from paludiculture is less than dairy farming and/or the NPV of the default scenario is negative, and therefore (yet) not attractive. If so, it is interesting to calculate what the carbon price (€ per t avoided CO_2) should be to have an NPV ≥ 0 (positive) or an equal average yearly net income of Dutch dairy farming and paludiculture. This will be analysed by trial-and-error.

5. Intermediate results: Functional unit

A direct result from the chosen methodology is the area division in the two systems as presented in Figure 15. This enables quantification of the functional unit of the system comparison.

In the reference system (RS), an average amount of 2.15 cows ha^{-1} on grassland is assumed with a yield of 8960 milk cow^{-1} yr^{-1}, based on the reference year 2018. This gives a total of 19264 kg milk ha^{-1}. This data is obtained from the Dutch Agro & Food portal from Wageningen University & Research (Agrimatie, n.d.) for the Agriculture FADN, which is an European Farm Accountancy Data Network for evaluating the income of agricultural holdings and the impacts of common agricultural policy. The study's structure requires that in the alternative system (AS), the same amount of milk is produced on set-aside land.

Moreover, the produced bio-insulation material on 1 ha peatland is based on the yield of cattail in the alternative system. The f.u.$_{\text{insulation}}$ (mass of one plate to obtain an R of 1 m^2 K/W) is calculated to be 1.60 kg. Following from Figure 19, there is an assumed cattail yield of 7.3 t ha^{-1}. Thus, a total of 4569 kg insulation plates with an R of 1 1 m^2 K/W. can be produced. With the assumed density of 50 kg/m^3, a total of 91 m^3 insulation material with an R of 1 1 m^2 K/W. can be produced.

m^2·K/W

The study's structure requires that in the RS an equal amount of insulation material with the same thermal resistance (mixture of glass/stone wool) is produced. In other words, an *y* kg of wool material is needed with the same R (=1 m^2 K/W.). This can be calculated following the steps in Figure 22 starting at 'Start'.

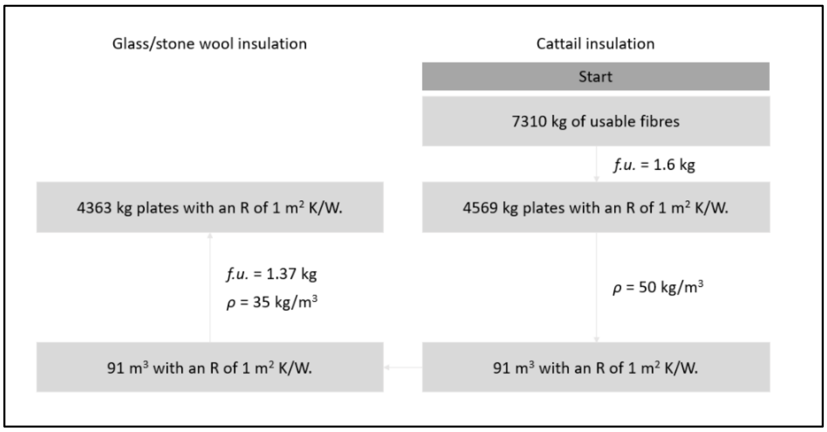

Figure 22: Calculation of the needed kg of insulation material with an R of 1 m^2 K/W in the reference system.

Thus, this results in 4363 kg wool insulation material with an R of 1 m^2 K/W.

In total, it can be said that the functional unit is the provisioning of 19264 kg milk with of Fat and Protein corrected (FPCM) with 4% fat and 3.3% protein (=*x*) and 91 m^3 of insulation material with a thermal resistance *R* of 1 (m^2 K/W) (=*y*) insulation material.

6. Results: LCA

6.1 Impact assessment: Dairy farming and insulation

The impact assessment of dairy farming (RS and AS) and the insulation material (AS: wool insulation, RS: cattail insulation) will be discussed. The impact assessment of cattail is discussed more in detail as this was one of the main goals of this research. In Section 6.3, a system overview is given of the impacts, thereby combining the impacts from the dairy farming and the insulation in relation to the f.u.

6.1.1 Dairy farming

Reference system: Dairy farming on Dutch peatlands

The average carbon footprint of Dutch dairy farms of the years 2011-2017 is used as reference value, which gives a value of 1.23 kg CO_2.eq/f.u.$_{milk}$ (Doornewaard et al., 2017). To illustrate the share of the different categories in the carbon footprint, an example of the carbon footprint of the year 2017 is given in Figure 23. The share of the categories in the other consulted years (2011-2016) are comparable, of which the corresponding data is added in Figure 34 in Appendix 2.

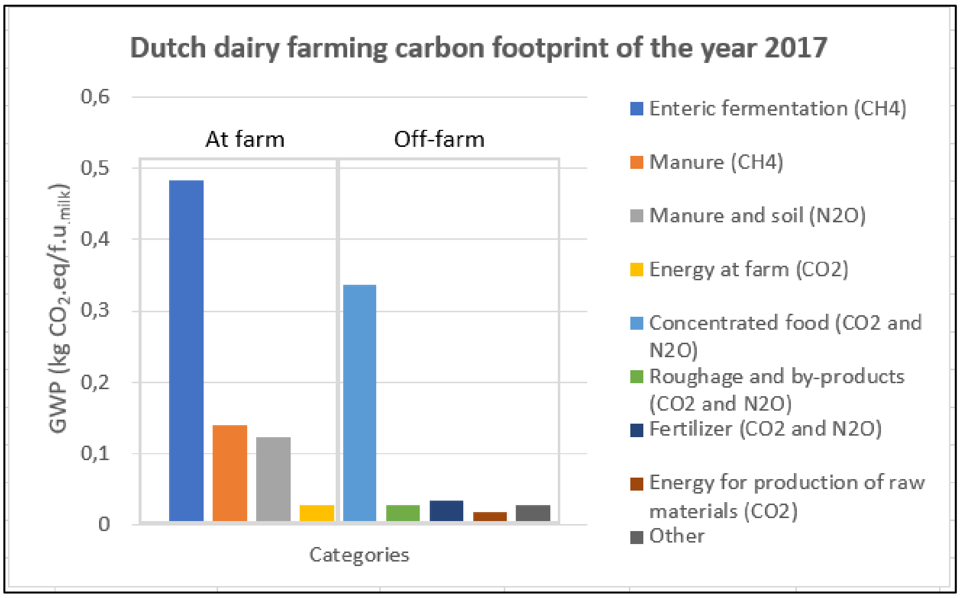

Figure 23: Carbon footprint of Dutch dairy farming for the year 2017 (Doornewaard et al., 2017). An allocation GHG-procedure of 85% for milk production and 15% meat is applied, cradle-to-farm.

Figure 23 reveals that 63% of the product carbon footprint is related to the activities on the dairy farm itself, which includes the first four categories (enteric fermentation, manure, manure and soil and energy at farm). This concerns in particular methane emissions from enteric fermentation of cows (40% of the total GWP). Producing and transporting of resources (off-farm, the remaining five categories) are associated with 37% of the GWP. The main contributor is producing and transporting of concentrated food, with roughly 27% of the total GWP of Dutch dairy farming.

To conclude, the enteric fermentation and the production and transporting of concentrated food are the two main contributors to the GWP of dairy farming, with a combined total of 67% of the GWP, followed by emissions from animal manure as a result of fermentation processes (11%) and emissions from manure and soil as a result of nitrification and denitrification processes in the storage of livestock manure and in the soil (10%).

Overall, to produce 19264 kg milk (produced on 1 ha), this results in a GWP of 23.69 t CO_2.eq ha^{-1}.

Alternative system: Dairy farming on set-aside land in Western-Europe

The f.u.$_{milk}$ on set-aside land in Western Europe is 1.29 kg CO_2.eq/f.u.$_{milk}$. This includes the milk production and the land use change. To produce 19264 kg milk (produced on 1 ha), this results in a GWP-impact of 24.85 t CO_2.eq ha^{-1}.

6.1.2 Insulation material

Reference system: Glass/stone wool insulation

The total GWP/f.u. in the reference system is 3.44 kg CO_2.eq/f.u.$_{insulation}$ (Figure 24). The two GWPs in Figure 24 represent the GWP per 0.69 kg of insulation material, as the f.u.$_{insulation}$ is 1.28 kg. The production of glass wool is the process which contributes the most in this GWP, with a share of 69% and a GWP of 2.4 kg CO_2.eq/f.u.$_{insulation}$. The production of stone wool results in a significant lower GWP, with a share of 29% and a GWP of 1.0 kg CO_2.eq/f.u.$_{insulation}$. The end-of-life phase of the glass/stone wool mat as well as the transport phase is excluded in Figure 24 as their relative share is ≤1%. In the waste-scenario, landfilling is assumed, which results in a low GWP compared to the production phase.

Figure 24: GWP/f.u.$_{insulation}$ of glass and stone wool production. Data is obtained from EcoInvent, with a cut-off criteria of 2%. Transportation and end-of-life phases are excluded due to their low relative share in the total GWP (≤1%).

Overall, to produce 4363 kg of insulation with an R of 1 W/m. K, this results in an impact of 15.0 t CO_2.eq.

Alternative system: Cattail insulation

The impact assessment outcome from cattail insulation is explained in detail as this was one of the focus points for this research. The various categories in the cattail lifecycle have different inputs, outputs, units and therefore impact. At first, the production process is analysed separately as this process consists of different stages and related impacts. Afterwards, an overview of the impact in the different categories of the lifecycle of cattail to an insulation plate is presented. Lastly, the carbon sequestration (biogenic carbon uptake and below-ground biomass) is discussed. In the end, this gives the results for the GWP/f.u.$_{insulation}$.

Production process

The results of the GWP/f.u. for the production phase are summarised in Table 18 and Table 19.

Table 18: GWP/f.u. in the production process of cattail insulation plates. Data for the panel production (first column) is obtained from Zampori et al. (2013). The sources of impact characterization factors (GWP/unit) are added in column four.

INFORMATION			TOTAL PER PANEL		GWP/UNIT (KG CO_2EQ/UNIT)		SOURCE GWP/UNIT	TOTAL GWP (KG CO_2.EQ/F.U.)
Preparation and mixing of panel: Electricity								
0,0022	kWh/kg fiber	82% fibers	0,002	kWh	0.45	kg CO_2.eq/kWh	CBS (2018) – *Dutch CO2 emission factor electricity production*	0.0013
Energy needed for panel production								
0,16	kWh/kg panel energy (electricity)		0,256	kWh	0,45	kg CO_2.eq/kWh	CBS (2018)- *Dutch CO2 emission factor electricity production*	0.12

2,043	MJ/kg panel (natural gas)	3,2688	Nm³	1,884	kg CO2.eq/Nm³	CO_2 Emissie Factoren (2019) - *Dutch CO_2 emission factor for natural gas*	0.18
0,0012	g PE film/kg panel	1,92E-06	kg	3,01	kg CO2.eq/kg PE	EcoInvent	5.8E-06
Total							0.30

Table 19: GWP/f.u. to produce binder, fungicide and flame retardant. The GWP/unit factors are obtained from reference flows from EcoInvent.

		PERCENTAGE	KG/PANEL	GWP/UNIT (KG CO_2EQ/UNIT)		TOTAL GWP (KG CO_2EQ/F.U.)
Binder	Polyester	14%	0,224	1,39	kg CO2.eq/kg	0.31
Fungicide	Thiocarbamate	0.5%	0,008	11	kg CO2.eq/kg	0.09
Flame retardant	Borax	3.5%	0,056	1,66	kg CO2.eq/kg	0.09
Total						0.49

By combining Table 18 and Table 19, this results in an impact of 0.79 kg CO_2.eq/f.u.$_{\text{insulation}}$ for the production phase of the panels. The share of the different categories in the production phase is depicted in Figure 25. The share of the *electricity for the preparation and mixing of the fibres* and the *PE film* are excluded from Figure 25 as their share is less than 1%.

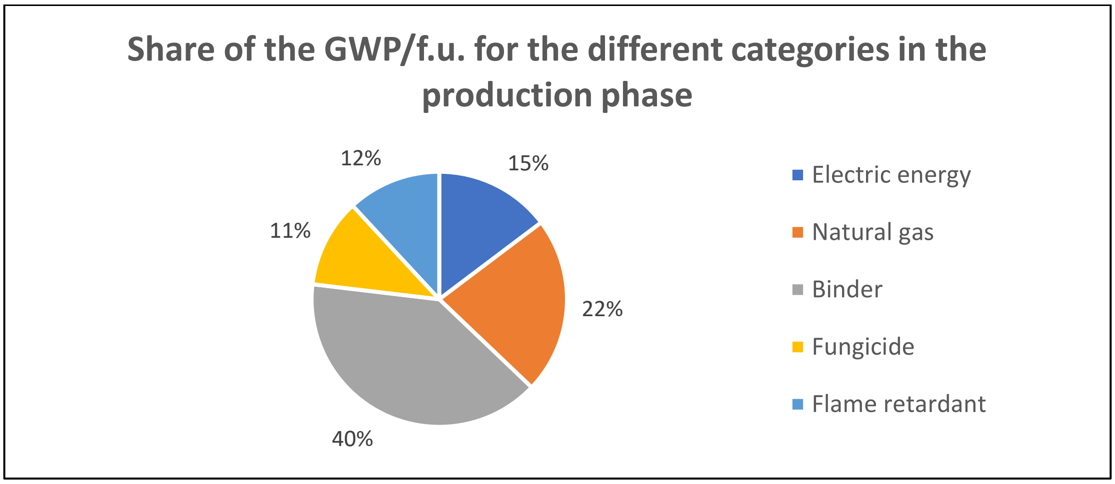

Figure 25: Share of GWP/f.u. in different categories in the production phase. Data is based on Table 18 and Table 19. Electricity for the preparation of the fibres and the PE film are excluded.

It can be concluded that the assumed additives (flame retardant, binder and fungicide) are large contributors to the GWP of the production phase. These additives are responsible for 63% of the total GWP, whereas the energy for the binding process (natural gas and electricity) only accounts for 37% of the GWP. More natural gas is needed than electric energy in producing the insulation plates. The largest contribution is the production of the polyester binder (40% of the GWP). This assumed polyester-completed starch polymer itself requires a large amount of fossil based energy and materials to produce. When zooming in this process, it is revealed that roughly 40% of the GWP of producing the polyester fibre is associated with the use of heat (natural gas) or (hard) coal.

Overview: Lifecycle of cattail without carbon sequestration

The production process as shown in the previous paragraph, is one part of the LCA of cattail insulation. The other lifecycle steps which are included in the system boundaries in the research should be added. These outcomes can be found in Table 20.

Table 20: Impacts calculated with GWP/f.u. to produce a cattail-based insulation panel. Impacts are divided for the production phases reported in Figure 17 (right image).

CATEGORY	INPUT DATA	UNIT	GWP/UNIT (KG CO_2EQ/UNIT)		SOURCE GWP/UNIT	TOTAL GWP (KG CO_2EQ HA^{-1})
Germination: planting	28.0	litre diesel	3.23	kg CO_2	CO_2 Emissie Factoren (2019) - *Dutch CO_2 emission factor for diesel*	91
Fertilization	200	kg NH_4-NO + application fertilizer	1647	kg CO_2	EcoInvent	1647
	25	kg P_2O_5 + application fertilizer	52.2	kg CO_2	EcoInvent	52
	200	kg KNO_3 + application fertilizer	603	kg CO_2	EcoInvent	603
Harvesting and mowing	236.8	litre diesel	3.23	kg CO_2	CO_2 Emissie Factoren (2019) - *Dutch CO_2 emission factor for diesel*	765
Windrowing	23.55	litre diesel	3.23	kg CO_2	CO_2 Emissie Factoren (2019) - *Dutch CO_2 emission factor for diesel*	76
Baling	49	bales	349	kg CO_2	EcoInvent	349
Transport 1	500	tonkm	0.10	kg CO_2	CO_2 Emissie Factoren (2019) - *Dutch CO_2 emission factor for tractor with heavy trailer*	51
Drying of the biomass	2922	Nm^3	1.88	kg CO2	CO_2 Emissie Factoren (2019) - *Dutch CO_2 emission factor for natural gas*	5505
Panel production	4569	f.u. = kg insulation with an R of 1 m^2 K/W	0.79	kg CO2/f.u.	See Table 18 and Table 19	3583
Transport 2	757	tonkm	0.11	kg CO_2	CO_2 Emissie Factoren (2019) - *Dutch CO_2 emission factor for lorry transport (20t)*	68
Total						12790

The impacts of the different process units during cattail cultivation (Figure 17, right image) per ha of cultivated land, so not considering biogenic CO_2 storage, are given in Figure 26. The GWPs associated with the rhizome planting are excluded as its share is < 1%.

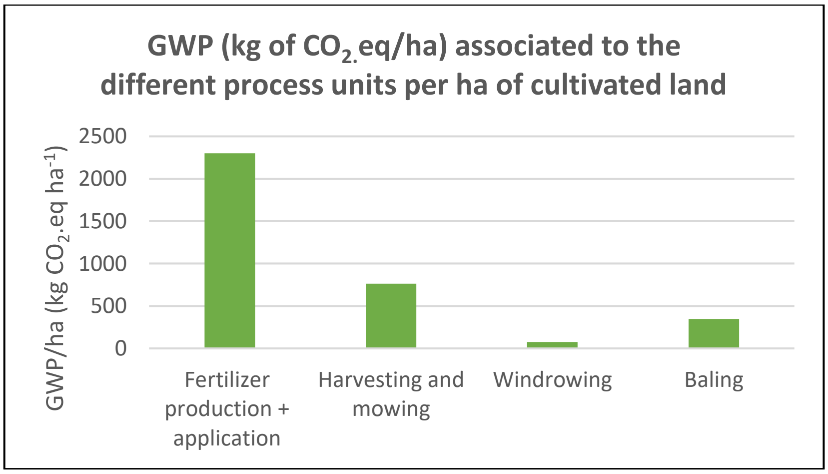

Figure 26: kg of CO_2.eq associated to the different process units per ha of cultivated land. CO_2 uptake is not considered. The shown categories are related to cattail cultivation (Figure 17, right)

Most GWPs during cattail cultivation are associated with fertilizer production and application, with the GWPs related to (the production of) ammonium nitrate (NH_4-NO) as main contributor.

The share of the GWP in the different production phase categories in the cattail lifecycle is depicted in Figure 27. The categories *rhizome planting, windrowing, transport of the baled biomass* (transport 1) and *transport from production place to customer* (transport 2) are excluded as their share is relatively low (≤1%). Together, these categories cover 2% of the GWP in the lifecycle of cattail insulation plates. It is assumed that the insulation plates are landfilled at the end of their lifetime, which is associated with no net CO_2-emissions. Drying of the biomass, with natural gas needed as energy, is associated with the largest GWPs of the different production phases, followed by the production phase.

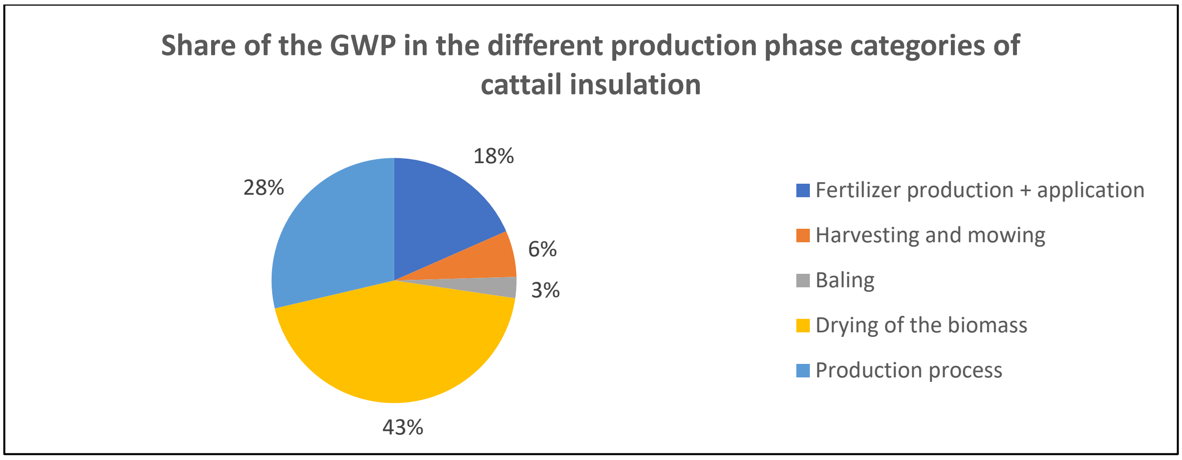

Figure 27: Share of the GWP/f.u. associated with the different production phase categories of cattail-based insulation plates. Shares are based on the proposed data in Table 20. Impacts are divided for the production phases reported in Figure 17 (right image).

Biogenic and below-ground carbon storage and delayed carbon emissions.

For the biogenic carbon storage in the insulation plates, the ratio CO_2/C and an average carbon content of 41.2% in cattail is assumed. The total biogenic CO_2-storage is 11.0 t CO_2, which is stored in the cattail fibres (from 1 ha) usable for the insulation plates (=7310 kg, see Figure 19). The delayed released method of the PAS2050 is used to deal with delayed carbon emissions. The biogenic carbon storage in the insulation plates should be multiplied by the weight factor for the use phase, which is 0.5. Therefore, the biogenic CO_2 following from the PAS-methodology is considerd to be 5.5 t CO_2. Moreover, there is a one-time carbon storage of below-ground biomass. The roots of cattail will capture carbon and it is assumed that there is no disturbance, e.g. the risk of carbon release is excluded.

The results for the categories of the below-ground biomass and the biogenic carbon (PAS2050) stored in the plates are summarised in Table 21.

Table 21: Below-ground and biogenic carbon storage (PAS2050) of cattail insulation plates. For details on assumption, see p.37 (Biogenic and below-ground) carbon storage, delayed carbon emissions and lifetime.

CATEGORY	QUANTITY	UNIT
Below-ground biomass	1.3	t CO_2.eq per ha
Biogenic carbon storage in insulation plates	5.5	t CO_2.eq stored in usable fibres (=7310 kg)
Total stored carbon	6.8	t CO_2.eq ha^{-1}

GWP/f.u. of life cycle assessment of cattail insulation

By using the GWP data proposed in Table 20, the GWP in terms of CO_2.eq per f.u.$_{insulation}$ can be calculated. To produce 4569 kg of insulation with an R of 1 W/m. K, this gives an impact of 12.8 t CO_2.eq. This results in an GWP-impact of 2.78 kg CO_2.eq/f.u.$_{insulation}$ when the biogenic carbon is excluded, and in an GWP of 1.29 kg CO_2.eq/f.u.$_{insulation}$ when the biogenic and below-ground carbon storage is included (PAS2050).

Comparison with other insulation materials

The lifecycle of cattail boards have been compared to the performances of replaceable or comparable products, based on previous research of Casas-Ledón et al. (2020) (Table 2). It can be noted that compared to PUR (5.1 kg CO_2.eq/f.u.) and expanded XPS (5.0 kg CO_2.eq/f.u.), the global warming potential of cattail fibres is considerably lower. These synthetic materials require large use of fossil fuels. It can be said that the LCA of cattail insulation results in a lower GWP compared to the conventional materials, as the mentioned PUR and XPS, as well as glass (9.8 kg CO_2.eq/f.u.) and stone wool (2.5 kg CO_2.eq/f.u.). Compared to unconventional materials, the global warming potential of cattail fibres excluding carbon storage is in the same order of magnitude with jute fibres (2.8 kg CO_2.eq/f.u.). The LCA of hemp cultivation (GWP: 1.13 kg CO_2.eq/f.u.), from the often-referred article of

Ardente et al. (2008) includes carbon storage and the results of cattail insulation are in the same order of magnitude compared to hemp, with only a small advantage to hemp.

6.1.3: Impact assessment: System analysis

The f.u. for this research is defined as the provisioning of 19264 kg milk with of Fat and Protein corrected (FPCM) with 4% fat and 3.3% protein (=*x*) and 91 m^3 of insulation material with a thermal resistance *R* of 1 (m^2 K/W) (=*y*) insulation material. Therefore, the two separate processes of dairy farming and insulation material (in both the reference and the alternative system) should be added to give an overview related to the f.u. This is depicted in Figure 28, of which the detailed data is added in Appendix 6 (Table 30 and Table 31).

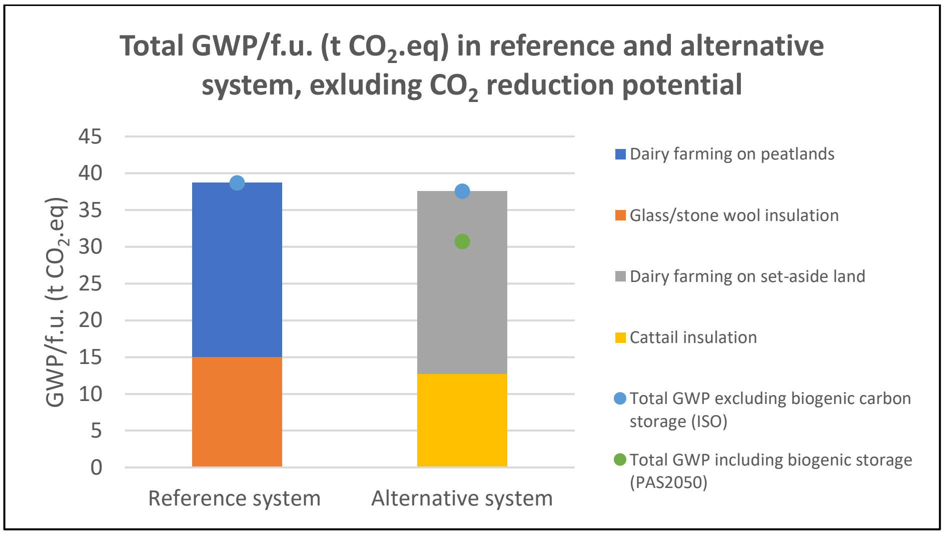

Figure 28: Total GWP (dairy farming and insulation material) in the reference system and alternative (without CO_2-benefits from rewetting peatlands). Boundaries are cradle-to-farm (dairy farming) and cradle-to-grave (insulation material). The impact of set-aside land in the reference system is excluded. Detailed data is added in Appendix 6.

It can be said that when comparing both systems (excluding biogenic CO_2), the total GWPs are almost equal. The system change from dairy farms on peatlands to set-aside land gives roughly the same GWP. The GWP for the mineral wool production is somewhat higher than cattail insulation. Substituting wool by cattail insulation is in terms of GWP slightly in favour of cattail insulation plates, with a system difference of 2.3 t CO_2.eq. The additional benefit from cattail insulation is the C-storage, including the biogenic storage results in even a larger difference of 9.1 t CO_2.eq when choosing cattail over wool insulation. Comparing the systems (excluding the biogenic storage) gives roughly the same GWP but including the biogenic storage results in a difference of 8 t CO_2.eq in favour of the alternative system.

6.2 Impact assessment: GHG peatlands

In Table 11, the used data for GHG emissions from peatlands related to the water level can be found. In West-Netherlands, most of the drained ha are within the category of 30-60 cm (AS3), and in North-Netherlands within the category -60 to -90 cm (AS2) or -90 to -100 cm (AS3) (see Figure 5). In Table 22, the results of the current GHGs emissions of peatlands is given, divided in the three most common categories in The Netherlands.

- Rewetting scenario 1 (AS1): from **-90 to -100 cm** towards 0 up to +20 cm (cattail-based paludiculture)
- Rewetting scenario 2 (AS2): from **-60 to -90 cm** towards 0 up to +20 cm (cattail-based paludiculture)
- Rewetting scenario 3 (AS3): from **30-60 cm** towards 0 up to +20 cm (cattail-based paludiculture)

Table 22: Summary of current GHG emissions (t CO2.eq ha^{-1} yr^{-1}) of Dutch peatlands. Data is obtained from Table 11 and associated sources.

CATEGORY DRAINAGE LEVEL	GHG EMISSIONS (T CO_2.EQ HA^{-1} YR^{-1})	AVERAGE GHG EMISSIONS (T CO_2.EQ HA^{-1} YR^{-1})
-90 up until -100 cm (AS1)	40.6 – 45.1	42.9
-60 up until -90 cm (AS2)	27.3 – 40.6	34.0
-30 up until -60 cm(AS3)	16.2 – 27.3	21.8

In the alternative system, an average water level of 0 to + 20 above groundwater level is assumed, which gives an average GWP-impact of 11.1 t CO_2.eq ha^{-1}. The emission reduction from one drainage category towards the drainage category associated with paludiculture cultivation can be found in Table 23. This includes the uncertainty adjustment of 10% (Equation 5). A range of the CO_2-reduction is given along with an average, which is based on the reduction potential with the minimum and maximum drainage depth. Moreover, the most common areas related to the drainage category are added.

Table 23: Range of emission reduction potential of GHGs from peatlands from conventional drainage depth to paludiculture (0 to + 20 cm). Data is based on current emissions related to water level (Table 11 and Table 22). Uncertainty margin: 10%.

FROM	TO	RESULTS IN	
REWETTING SITUATION		**RANGE OF GWP-PROFIT (T CO_2.EQ HA^{-1} YR^{-1}**	**AVERAGE**
	Elevated water level (0 to +20 cm)	*RANGE MIN:MAX*	
AS1: North-Netherlands		26.5 - 30.6	28.6
AS2: North-Netherlands		14.6 - 26.5	20.6
AS3: West-Netherlands		4.6 - 14.6	9.6

It can be concluded that the GWP-reduction depends on the starting situation (current drainage depth). The reduction potential is the highest related to system change AS1, with an average reduction of 28.6 t CO_2.eq ha^{-1} yr^{-1}. The (average) reduction potential decreases with less drainage. This indicates that the potential of a system change towards water levels associated with paludiculture is higher (in terms of CO_2.eq from peatlands) in areas which are currently deeply drained, mostly in North-Netherlands.

Urgenda, an organisation which aims to accelerate sustainability in The Netherlands, proposed an action plan with 40 elements that should be undertaken to achieve a 25% CO_2-reduction in 2020. One of these elements is accelerated rewetting of peat meadows. They also conclude that the northern peat areas come along with deeper drainage than in the rest of The Netherlands, which means that potentially more CO_2 savings can be achieved in northern areas. Their research concluded that at Frisian peat meadows (North-Netherlands), the CO_2-benefits could be up to 40 t CO_2.eq ha^{-1} yr^{-1} when peatlands are rewetted for paludiculture. At the Holland-Utrechtse peatlands (West-Netherlands), the CO_2-benefits are 20 t CO_2.eq ha^{-1} yr^{-1} .

The potential benefits from the study of Urgenda and the proposed carbon benefits in this research differ from each other. A benefit in North-Netherlands from 40 (Urgenda) and 28.6 (this research) t CO_2.eq ha^{-1} yr^{-1} is a significant difference. The same with the western area, of which Urgenda estimates a CO2 potential of 20 t CO_2.eq ha^{-1} yr^{-1}. The differences might be explained by different assumptions. The research of Urgenda assumes a slightly stronger relationship between CO2-reduction and water level, with 0.5 t CO_2.eq ha^{-1} yr^{-1} per cm groundwater level rise, which results in more CO2-benefits than in the model used in this research, with 0.45 5 t CO_2.eq ha^{-1} yr^{-1} per cm groundwater level rise. Moreover, they assume a larger CO_2-fixation in systems with accumulation of organic matter, namely 2.2 t CO_2.eq ha^{-1} yr^{-1}, which is more than the assumed 1.3 t CO_2.eq in this research. This shows that there are still uncertainties in modelling GHG-fluxes, which is further elaborated in Section 9: Discussion.

6.3 Change in GHG emissions due to altered peatland management

Overview of the impact assessment of the systems and the GHG from peatlands

The last step is to combine the results from the impact assessment of dairy farming, insulation material and the GHGs of peatlands and to give an overview of the changing GHG emissions of the reference and the alternative systems. The results of the GWP in the reference system and the three alternative systems (related to the three main drainage depth categories) are depicted in Figure 29. Two statements should be made:

- An average GWP-reduction potential (Table 23) for peatlands from different rewetting situations (AS1-AS3) is used in the alternative scenarios.
- The GWP including the biogenic carbon storage is calculated by subtracting the carbon storage (Table 21) from the GWP excluding the carbon storage.

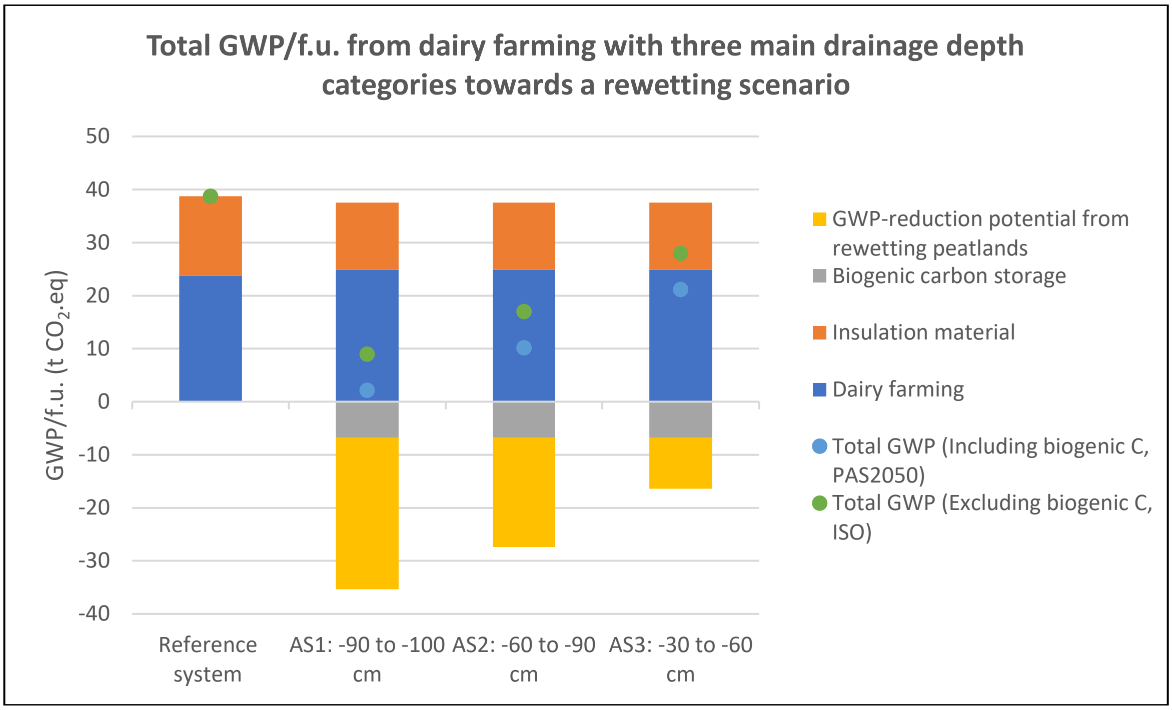

Figure 29: Total GWP from system changes from three main drainage categories towards a system with paludiculture. In the reference system, insulation refers to glass/stone wool and dairy farming to Dutch dairy farming on peatlands. In the alternative systems, insulation refers to cattail insulation and dairy farming to dairy farming on set-aside land. Landfilling is assumed at EoL. Biogenic CO_2 is stored for 50 years and released afterwards (delayed released method PAS2050, time-horizon 100 years) Associated data can be found in Appendix 6 (Table 32).

It can be concluded is that a system change from (deep) drainage to a water level associated with cattail-based paludiculture results in a decrease in GWP/f.u. in all alternative systems. The difference between the reference system and alternative systems are 29.7, 21.7 and 10.7 t CO_2.eq ha^{-1} for AS1, AS2 and AS3 respectively (excluding biogenic carbon storage). Including the biogenic storage (PAS2050) even results in a greater reduction of GWP/f.u., with approximately 7 t CO_2.eq stored in the cattail insulation plates.

The negative contributions in the GWP/f.u. in a system change from areas with deep drainage (AS1) can be mainly attributed to the avoided GHG emissions from peatlands. This relative benefit of avoided GHG emissions from rewetting peatlands decreases with a s system change with currently relatively low drainage, with this relative benefit in AS3 almost equal to the benefits of the biogenic carbon storage.

6.4 Interpretation

The goal of this study was to compare the potential environmental impacts of two methods of utilizing presently used peatlands providing either milk or insulation material. These GWP-impacts are clearly visualised in Figure 29. The results provide guidance to critically consider current and future land use on peatlands from a climate's perspective. Statements regarding the level of confidence of the proposed LCA are given in Section 9 (Sensitivity analysis). In this section, the relevance of initial assumptions and accounting methods during the inventory phase are discussed. For example, allocation rules, assuming different reference values or disposal scenarios are estimated to play a role.

7. Results: Commercial viability of paludiculture

7.1 Default scenario: Paludiculture without carbon credits

Dairy farming

Following from Table 12, there is an average income of €8.35 per 100 kg milk (period: 2001-2009), which is divided into revenues, costs and non-allocated costs (Vogelzang & Blokland, 2011). In this business case, it is assumed that a dairy farm on grasslands with Holstein-Frisian cows has a profit of roughly 33 Euro per 100 kg milk. Currently, the price of milk is 36 Euro per 100 kg, so this is in the same order of magnitude.

The total income for Dutch dairy farming with an average yield of 19264.0 kg milk is summarised in Table 24.

Table 24: Average income from Dutch dairy production on grassland from the period 2001-2009. Revenues are based on a price of 33 euro per 100 kg milk (Vogelzang & Blokland, 2011). Associated detailed data is added in Appendix 5 (Table 29).

	PER 100 KG MILK	FOR 19264 KG MILK
Revenues	42.35	
Costs	12.09	
Non-allocated costs	21.91	
Total	8.35	1608.54

Cattail-based paludiculture

The viability is divided for the regions North and West Netherlands. The estimated yearly costs and benefits for North-Netherlands are depicted in Figure 30. Detailed data is added in Appendix 7 (Table 33). West-Netherlands has a slightly higher land rent (€796 ha^{-1} compared to €646 ha^{-1} in North-Netherlands), but the other categories are equal compared to North-Netherlands. Therefore, Figure 30 is to a large extent also representable for West-Netherlands.

During year 1, there are no profits from selling the cattail fibres. It is assumed that the revenue linearly increases from year 2, and a maximum revenue of €3400 is achieved at year 5. This is based on the experience from the longest Dutch pilot project running, which is currently six years. For the years 2-4, it is assumed that 50% of the total costs for harvesting, windrowing, transportation and related labour costs apply because of the lower assumed yield in these years. The benefits are based on the price the producers are willing to pay for processed fibres material (Van de Riet et al., 2014).

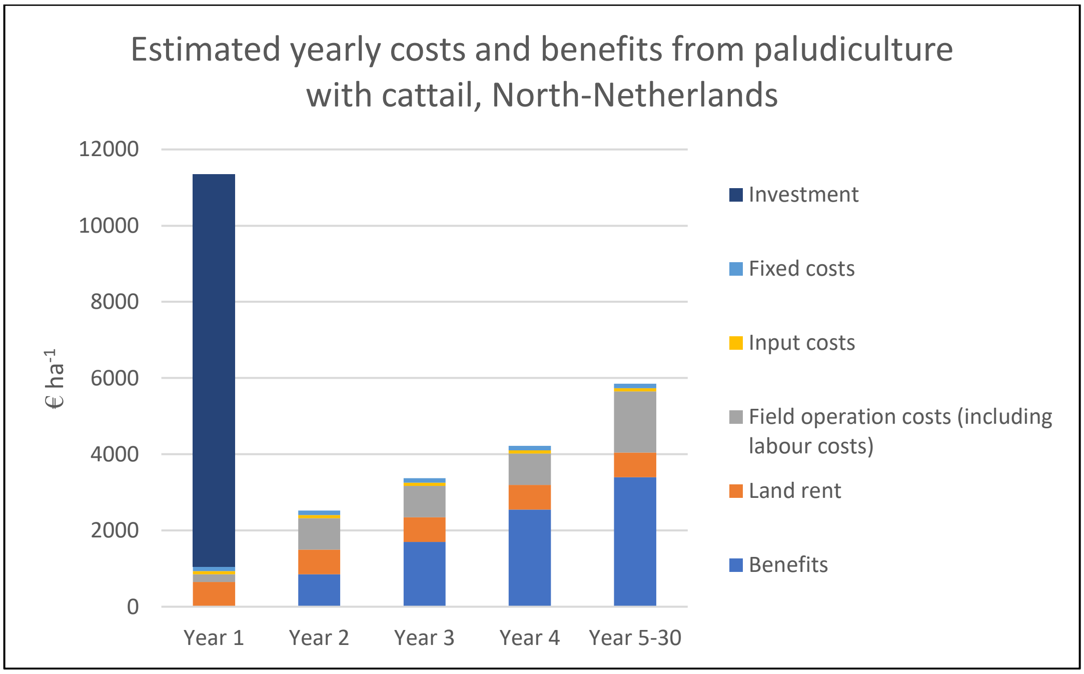

Figure 30: Estimated yearly costs and benefits (€ ha^{-1}) from cattail-based paludiculture, North-Netherlands. Detailed data is added in Appendix 7.

The high field operation costs are in the same order of magnitude with previous literature from Van de Riet et al. (2014), who assume approximately €2000 ha^{-1} yr^{-1} for harvesting costs (in this research defined as field operation costs) of paludiculture. The fixed costs and input costs are relatively small compared to the other cost categories as field operation costs and land rent. The investment costs, equal to €7300 ha^{-1} cover a large part of the (initial) costs.

Comparison of income of paludiculture with dairy farming

When comparing the costs and benefits from Dutch dairy farming with paludiculture (Table 25), it is revealed that the current income from dairy farming on Dutch peatlands is higher than paludiculture. This can be explained by the relatively low benefits from cattail from paludiculture combined with the high field operation costs, which gives a loss in the first years. The average net income per year is higher in the northern part than in the western part of The Netherlands (Table 25) due to lower land rent costs.

Table 25: Comparison of average net incomes (€ ha^{-1}) from Dutch dairy farming and cattail-based paludiculture.

		€ HA^{-1} YR^{-1}
Dairy farming		1608.54
Paludiculture		
	North-Netherlands	790
	West-Netherlands	640

When comparing the income from year 5 onwards, thereby excluding the less benefits in the first four start-up years, this still results in less income for paludiculture. This results in approximately €950 ha^{-1} for the northern part, and €800 ha^{-1} for the western part.

NPV

The commercial viability of paludiculture is assessed by calculating the NPV with an annuity period of 30 years and a discount rate of 6%. The reasons behind these chosen values are explained in Section 4.3. This NPV is calculated from the farmers' point of view, so not the producent. Calculating the NPV from the producers' point of view is outside the scope of this research.

The NPV of cattail is found to be slightly negative when all costs, benefits and the investment are included (Figure 31). Again, this can be mainly attributed to the high field operation costs of paludiculture related with high labour costs.

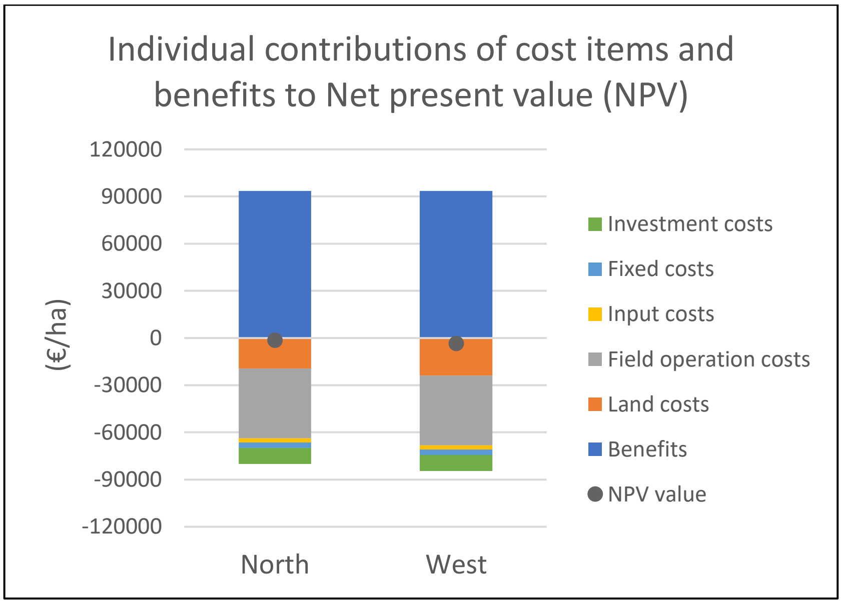

Figure 31: NPV of cattail from paludiculture, North- and West-Netherlands. Calculated with a project lifetime of 30 years, discount rate 6%.

The analysis reveals that the NPV in North-Netherlands (€-1535 ha^{-1}) is higher than in West-Netherlands (€-3600 ha^{-1} due to the lower costs for land. In North-Netherlands, the benefits exceed the costs from year 3 (investment excluded). In West-Netherlands, this occurs from year 4 onwards.

7.2 Alternative scenario: Paludiculture with carbon credits

The default scenario does not include valuing the damage of GHG emissions by carbon credits. In this section, it is tried to assess the influence from these carbon credits on the viability of paludiculture. Again, these carbon credits are only attributed to the emission reduction potential of peatlands related to the higher water level.

It is decided to assess this influence for North-Netherlands. North-Netherlands is chosen over West-Netherlands for three reasons: (1) the previous results show that the NPV is higher in this region and (2) the potential GHG reduction from peatlands is higher in this region due to current deeper drainage. The third one (3) relates to willingness to switch to alternative farming on Dutch peatlands. A short interview with the Natuur & Milieu Federatie (personal communication, February 10, 2020), who investigates the development of a carbon credit system in Dutch peatlands, revealed that the willingness to adopt paludiculture could be higher in the northern part than in the western part. The current water level in the northern part is lower due to deep drainage and this deep drainage leads to difficulties with current farming practices. The willingness to switch to another management practice with less difficulties is therefore expected to be higher in areas with a deep drainage level than in areas with less deep drainage (and as a result less difficulties for their current farming). Thereby, the profits from carbon credits in the northern part are expected to be higher due to a higher GHG reduction potential (see reason 2), which contributes to the willingness. In North-Netherlands, areas are mostly drained in the category -60 to -90 cm or -90 to -100 cm. For this analysis, the system change from the drainage category -60 to -90 cm (AS2) to paludiculture is investigated, which is the ***reference scenario*****.**

One side note to mention regarding valuing the GHG externalities is that the calculated carbon benefits from paludiculture are currently only calculated based on the CO_2-benefits from rewetting the peatlands. The revenues of these credits are awarded to the farmer itself and in this scenario, the producers (and in the end the consumers) do not directly profit from these credits. The biogenic storage is excluded from carbon credits but valuing these avoided GHG emissions might be more awarded towards producer and consumers. This is further discussed in Section 9.2.

Following from Table 23, an average of 20.6 t CO_2.eq ha^{-1} yr^{-1} can be expected due to the elevation of the water level in North-Netherlands. The total GHG reduction for 30 years is calculated by using Equation 6. The outcomes are summarised in Table 26.

Table 26: Project (=30 years) GHG reduction potential from AS2, North-Netherlands.

		CO_2.EQ REDUCTION	
		t CO_2.eq ha^{-1} for 30 years	
	MIN	MAX	AVERAGE
Dairy farming (-60 to -90 cm below water level) (=*reference*)	0	0	0
Paludiculture with cattail (AS2)	438	795	618

This results in the extra revenues from the compliance and the voluntary market resulting from Equation 7. Average values for the prices of the carbon commodities are used. It is assumed that these extra revenues are sold *ex-ante*. The results of the individual contributions of the cost items and benefits (including carbon credits) to the NPV are given in Figure 32. Detailed data on the revenues for carbon credits are added in Appendix 8 (Table 34 and Table 35).

It can be observed that the NPV increases with an increasing carbon commodity price. Besides, all calculated NPVs are positive when the revenues from carbon credits are added in the default scenario. Moreover, it can be concluded that even with a relatively low price of one carbon credit (compliance market, €7 per ton avoided CO_2-emissions), this results in a positive NPV for paludiculture. The results show that introducing a system as carbon credits could make possible investments in paludiculture attractive.

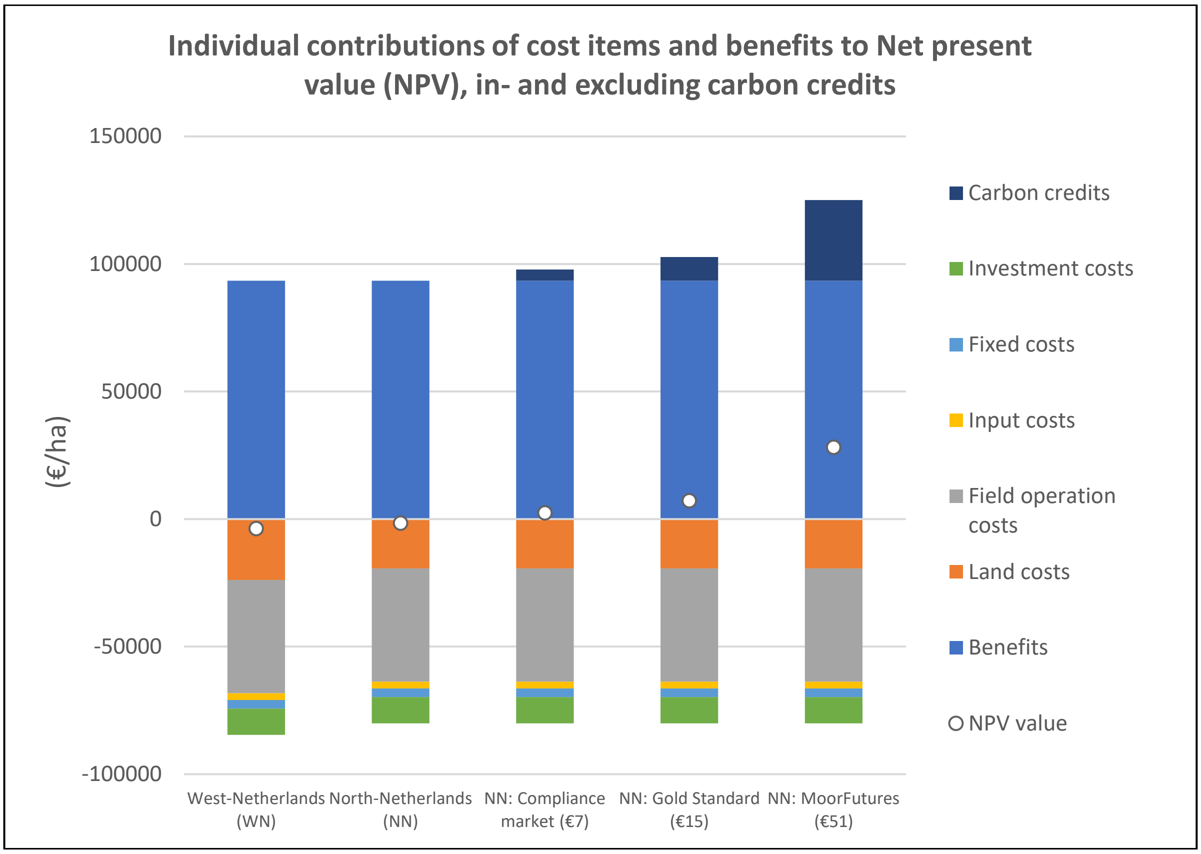

Figure 32: Individual contributions of cost items and benefits to Net present value (NPV) (project lifetime of 30 years, discount rate 6%), in- and excluding carbon credits. The carbon prices are 7, 15 and 51 € per ton avoided CO2 for the compliance market, Gold Standard and MoorFutures respectively. Valuing GHG emissions is done by adding carbon credits only in the NPV of North-Netherlands (current drainage: -60 to -90 cm) due to higher economic feasibility in this region. For the carbon credits, an average carbon benefit of 20.6 t CO_2.eq ha^{-1} yr^{-1} is assumed. Detailed data is added in Table 34 and Table 35 in Appendix 8.

7.3 Carbon breakeven price for the income and NPV from paludiculture

Another interesting aspect to analyse is the price of the carbon commodity at which the incomes of paludiculture are equal to dairy farming, as well as the carbon breakeven price at which the NPV is positive.

Carbon breakeven price: Income

As previously calculated in Table 25, the current incomes for Dutch dairy farming are approximately €1600 ha^{-1}, whereas the average net yearly income from paludiculture are approximately €800 ha^{-1} in North-Netherlands. Therefore, to compete with dairy farming on peatlands, additional yearly revenues from carbon credits are needed. By trial-and-error, assuming an average yearly carbon benefit of 20.6 t CO_2.eq ha^{-1} yr^{-1} and observing the changing income, this results in a **yearly carbon commodity price between the €39 and €40 per ton avoided CO_2-emissions** in order to compete with dairy farming.

Interestingly, this calculated carbon breakeven price is in line with the price of excess Dutch carbon emissions as proposed in the Dutch Climate Agreement of 2019. Calculated by the PBL, the CO_2 price for Dutch industry will start at approximately €30 per ton in 2021. The analysis of paludiculture shows that when implementing the carbon price from the Dutch Climate Agreement, paludiculture is an interesting mitigation option.

Carbon breakeven price: NPV

The carbon breakeven price is also relevant for the NPV. As revealed, even a price of €7 per t avoided CO_2.eq (compliance market) gives a positive NPV. By trial-and-error and observing the changing NPV, it is revealed that **a carbon breakeven price of €2.64 per t avoided CO_2.eq for a project period of 30 years** is sufficient to obtain a positive NPV-value.

8. Upscaling: Estimation of potential GHG benefits from paludiculture for Dutch peatlands

Lastly, it is interesting to zoom out from 1 ha peatlands to the total area of peatlands in The Netherlands (approximately 270.000 ha, Bodemkaart (2014)) and give a rough estimate of the potential environmental benefits from a system change on a larger scale.

The most common drainage category is 30-60 cm (34%), followed by >90 cm (21%) and 60-90 cm (19%) (Van den Born et al., 2016). It is thus assumed that there is 91.800 ha peatlands in the drainage category -30 to -60cm, 51.300 ha in the category -60 to -90 cm and 56.700 ha in the category >-90cm. The rest of the peatlands are within drainage categories which are not considered in this research.

Two scenarios are assumed, one with 10% of the current peatlands which adapt the system change to paludiculture with cattail, and one with 30%. The scenario of 10% is based on previous research of Planbureau voor de Leefomgeving (PBL) (Van den Born et al., 2016) in which they also assume a transition of peatlands to either nature or paludiculture with 10% of the researched peatlands. A scenario of 30% is highly speculative and based on an optimistic view of the future, and (yet) not investigated in previous research. The assumed data is summarised in Table 27.

Table 27: Estimate of the total environmental benefits for a system change of Dutch peatlands towards a paludiculture system (including biogenic carbon storage). Current peatlands areas is based on shares of drainage depth categories in Van den Born et al., 2016). Total estimated peatland area is 270.000ha.

REWETTING SITUATION AND CORRESPONDING AREA IN NL	**CURRENT PEATLAND AREA (HA)**	**PROPOSED AREA WITH PALUDICULTURE (HA)**	
		S1	S2
		10%	30%
West-Netherlands			
AS3: -30 to -60 cm	91.800	9180	27.540
North-Netherlands			
AS2: -60 to -90 cm	51.300	5130	11.390
AS1: -90 to -100 cm	56.700	5670	17.010

Afterwards, the total environmental benefits from system changes of the reference system towards AS1, AS2 or AS3 can be calculated (Table 28):

- The total GWP/f.u. in the reference system is based on the calculation that the GWP/f.u. in the RS is 38.7 t CO_2.eq, multiplied by the assumed current peatland area in the two scenarios from Table 27.
- The total environmental benefits are based on the difference between total GWP/f.u. in the reference system minus the total GWP/f.u. in the alternative system(s). Assumed GWP/f.u. of AS1, AS2 and AS3 are 2.2, 10.2 and 21.2 GWP/f.u (including biogenic CO_2).

Table 28: Environmental benefits (Mt CO_2.eq yr^{-1} from system changes on a larger scale (10% and 30% of peatlands implementing paludiculture in AS1, AS2 and AS3).

	TOTAL GWP IN REFERENCE SYSTEM (MT CO_2.EQ)	**TOTAL ENVIRONMENTAL BENEFITS FROM THE SYSTEM CHANGE (MT CO_2.EQ YR^{-1})**	
		S1	S2
		10%	30%
AS3	0.35	0.16	0.48
AS2	0.20	0.15	0.44
AS1	0.22	0.21	0.51
Total: Best case scenario		0.51	1.43

The calculated environmental benefits from the two scenarios should not be added but should rather be read as *if X % of the peatlands switches from drainage category X to paludiculture with cattail, this could save X Mt* CO_2*.eq yr*$^{-1}$*.* For example, if 10% of the peatlands switches from the drainage category -60 to -90 cm (AS2) to paludiculture, this could save 0.15 Mt CO_2.eq yr^{-1}. In the last row, a total of the benefits for each scenario are added, which can be seen as *best-case scenario*. This indicates for example that if all areas/drainage categories rewet e.g. 30% of their peatlands for paludiculture, this could save 1.43 Mt CO_2.eq yr^{-1}. Combining areas with different drainage level is also possible, but this is not investigated in this research.

Rewetting peatlands and implementing a system change in West-Netherlands (AS3) could save 0.16 Mt CO_2.eq yr^{-1} (10% of the peatlands) to 0.48 Mt CO_2.eq yr^{-1} (30% of the peatlands). Rewetting larger areas (30%) in northern parts of The Netherlands might be more promising in terms of environmental benefits, where deeper drainage is occurring. With 30% of the peatlands (AS1 and AS2) switching to paludiculture, this could result in a minimum of 0.44 to a maximum of 0.51 Mt CO_2.eq yr^{-1} depending on the drainage category. Moreover, following from the performed analysis of the commercial viability of cattail, it is also revealed that the economic feasibility of paludiculture is higher in North- than in West-Netherlands. Concluded, the potential of rewetting (larger) areas as well as the environmental benefits is higher in northern parts of The Netherlands.

The study of PBL (Van den Born et al., 2016) states that when rewetting 10% of the complete study area (study area = 200.000 ha) towards paludiculture results in an avoided emission of 0.4 Mt CO_2.eq yr^{-1}. This is slightly less than the calculated 0.51 Mt CO_2.eq yr^{-1} in this research when rewetting 10% of the investigated peatlands in AS1, AS2 and AS3. The previous mentioned research of Urgenda (2020) focusses on accelerating rewetted peatlands but focusses at achieving this by elevating the water level within realised/soon to be realised nature areas (Natuur Netwerk Nederland). A comparison with this research is therefore not possible.

At last, in last years presented Climate Agreement, there is a reduction target of 1 Mt CO_2.eq yr^{-1} for Dutch peatlands by 2030 (Urgenda, 2020). The analysis shows that rewetting peatlands could significantly contribute to this target. Even with only rewetting 10% of the peatland's areas in each RS, the reduction target could be halfway met.

9. Discussion

9.1 Sensitivity analysis

According to Ardente et al (2008), results of an LCA do not represent exact or precise data as they are affected by several uncertainties. This might be due to a lack of data of the assumptions made in the inventory analysis. Therefore, a sensitivity analysis should be performed, which aims to assess the effects of the chosen methods, assumptions and data on the outcome of the study (Ardente et al., 2008).

A sensitivity analysis is performed with several scenarios relating to the LCA and cost-benefit analysis. In this analysis, the following parameters are identified as key parameters (Table 33). Other parameters related to input data are also analysed but have a minor effect on the results. These parameters have been selected because of expected fluctuations or uncertainty in specific parameters (e.g. discount rate, production process, commodity prices) and/or expected effect of the key parameters on the results (e.g. yield or project lifetime). The proposed scenarios are summarised in Table 29.

Table 29: Scenarios and key parameters for the sensitivity analysis for the LCA and the Net Present Value (NPV).

SCENARIO	PARAMETER	EXPLANATION
1	By-products as low quality forage	The rest products and the rejected fibres (1500 kg) are used as low-quality forage. Concluding from the research of Pijlman et al. (2019), the harvest of broadleaf cattail later in the season could be used as fibrous roughage at low dietary inclusion rates. The avoided burdens of the production of the low-quality forage is estimated to be 0.237 kg CO_2.eq/kg product with the reference process of '*grass silage at dairy farms'* in The Netherlands, obtained from the Agri Footprint database. No activities are considered, besides wrapping of the silage in foil and the effect of drying of the grass on the mass. The nutritional quality is relatively low compared to grass silage (Pijlman et al., 2019), so the reference process of grass silage is chosen over higher quality forage mixes.
2	End-of-life: Fibre board treated as waste wood	The plates are treated as waste wood and incinerated. The reference flow from EcoInvent *Waste wood, untreated (RoW), treatment of waste wood, untreated, municipal incineration* is used. The boards go to disposal as part of communal waste mixture and this generates heat with an upper heating value of 15.36 MJ/kg.
3	Fluctuations in the yield of dairy farming	The yield of dairy farming from 1 hectare is based on assumptions as cows ha^{-1}. Fluctuations in the yield of milk and in this way the related carbon footprint are modelled, with -25% (3a) and +25% (3b) from the current value (19264 kg FPCM-milk). This value is chosen as another research (Van den Ham, Daatselaar & Doornewaard, 2013) on Dutch dairy farming varies roughly 25% of the used reference value in this research, concerning yield of milk.
4	Conventional insulation material (glass/stone wool)	In the reference system (RS), an equal share of wool insulation (mixture of glass/stone wool) is assumed. An adjustment could affect results, as the LCA of the proposed mixture reveals that the GWP for glass wool is considerably higher than stone wool (Figure 24). Therefore, two scenarios are analysed with the conventional insulation material completely derived from one insulation material, namely one with glass wool (4a) and stone wool (4b).
5	Uncertainty in drying of the biomass	Drying of the biomass has a relatively impact within the production process (43% of the GWP in the different production phase categories of cattail insulation), although the process is based on the average energy use per ton dehydrated forage is used. The effect of an increase (5A) or decrease (5B) of this parameter could therefore influence the results.
7	Discount rate	The assumed discount rate is 6%. The discount rate has declined over recent years and thus a decreased interest rate of 2% (7A) and 4% (7B) are analysed.
8	Project lifetime	The assumed project lifetime is 30 years. For rewetting projects, this is a minimum (rewetting projects are usually 30-50 years (Van de Riet et al., 2014). A time horizon of 30 years might however also be a relatively long-term goal for investors. Therefore, two

		alternative project lifetimes of 20 years (8A) and 40 years (8B) are analysed.
9	Benefits from selling the cattail fibres	The chain of cattail insulation is not fully developed yet, and this results in an uncertainty margin for benefits and costs. The costs are now based on the price the producer is willing to pay, which varies between €300 and €400 per t DW and based on previous research (Van Duursen & Nieuwenhuijs, 2016). Therefore, a bandwidth of -25% (9A) and +25% (9B) is analysed.

The results of the various scenarios are divided for the LCA (Figure 33 and Figure 34) and cost-benefit analysis (Figure 35). For the LCA, the sensitivity analysis is divided in GWP/f.u.$_{\text{insulation}}$ and the system's f.u. of the provisioning of milk and insulation from 1 ha (GWP/f.u.) in the reference or alternative system. The percentual increase or decrease of the observed values from the sensitivity scenarios compared to the default scenarios are given. Detailed data is added in Appendix 9 (Table 37).

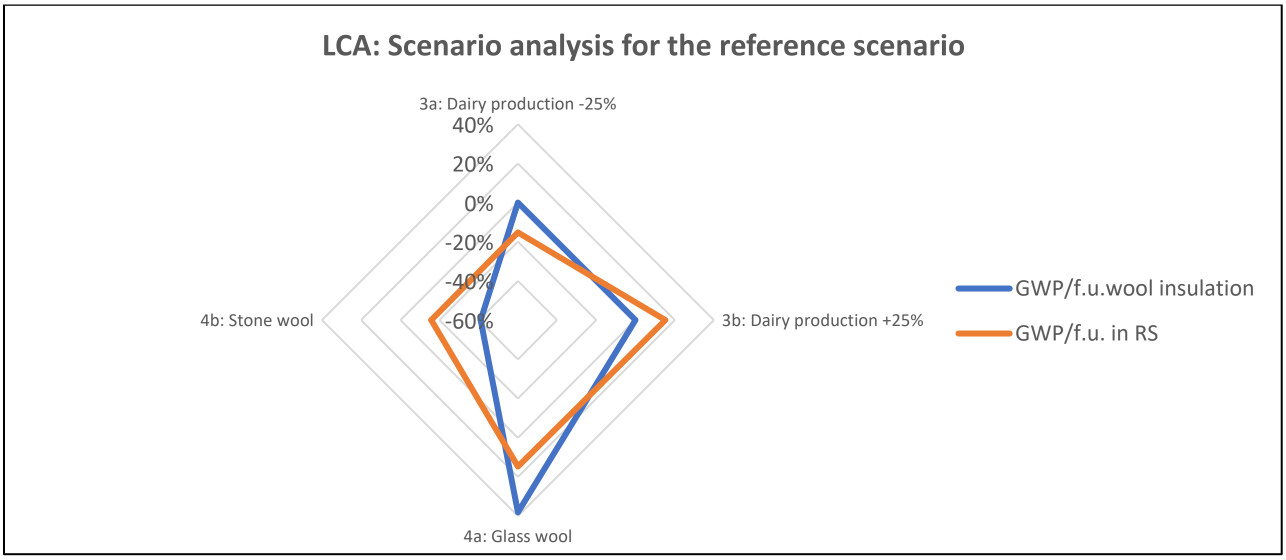

Figure 33: Percentual in- or decrease from the proposed sensitivity scenarios (LCA) relative to the default values, reference system. Detailed data is added in Appendix 9.

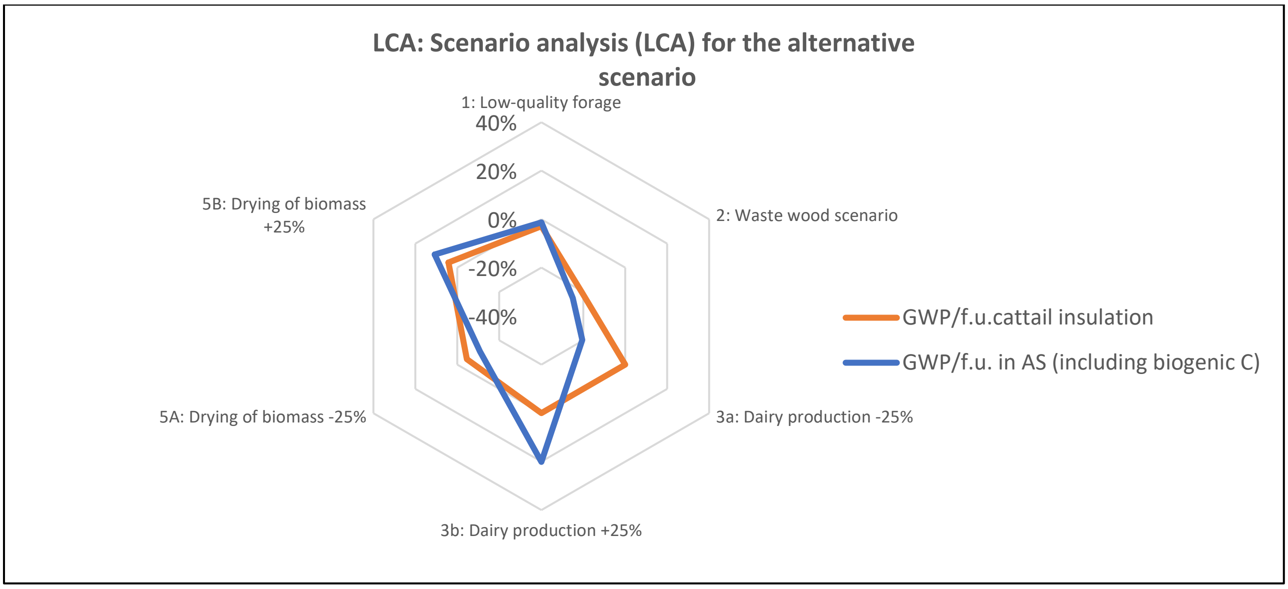

Figure 34: Percentual in- or decrease from the proposed sensitivity scenarios (LCA) relative to the default values, alternative system. Detailed data is added in Appendix 9.

It can be concluded that the choice of the wool insulation mixture has a great influence on GWP/f.u.$_{\text{insulation}}$, and therefore greatly influences the GWP/f.u. This effect is slightly higher than assuming an increase or decrease of dairy production. Assuming a glass wool insulation mat results in a significant higher GWP/f.u.$_{\text{insulation}}$ than in the reference scenario, with an increase of roughly 40%. When assuming a stone wool mat, there is a relative decrease of the GWP/f.u.$_{insulation}$ with approximately 15%. A different assumption in the reference material affects the CO_2 balance in the RS, also depicted in Figure 33 by the orange rectangular for scenario 4a and 4a. Hence, the choice of the conventional reference material is crucial, and attention should be paid when choosing which conventional material (or which mixture) is replaced by cattail insulation. The GHG-reduction potential is significantly influenced by these assumptions.

Concerning the alternative scenario, three observations are relevant. First, it can be observed is that including by-products as low-quality forage (*system expansion*) has not a large effect on the GWP/f.u. Secondly, assuming a different end-of-life, with cattail treated as waste-wood, results in a percentual reduction of 21% in GWP/f.u.$_{insulation}$ and 25% in GWP/f.u. A decrease of roughly ¼ or ⅕ compared to the reference value can be considered as relative large decrease, and this does confirm that as also described in the Theory, disposal phase might be a large contributor (or, in this case reducer) to carbon emissions (Casas-Ledón et al., 2020). Lastly, assuming a higher or lower yield for milk also effects the GWP/f.u. with an in- or decrease of 20% compared to reference value.

The sensitivity analysis for the NPV is performed for scenario AS2 (North-Netherlands, from -60 to -90 cm towards a water level of 0 to +20 cm), with a default NPV of €-1535 ha^{-1}. Carbon credits are excluded. Detailed data is added in Appendix 9 (Table 37).

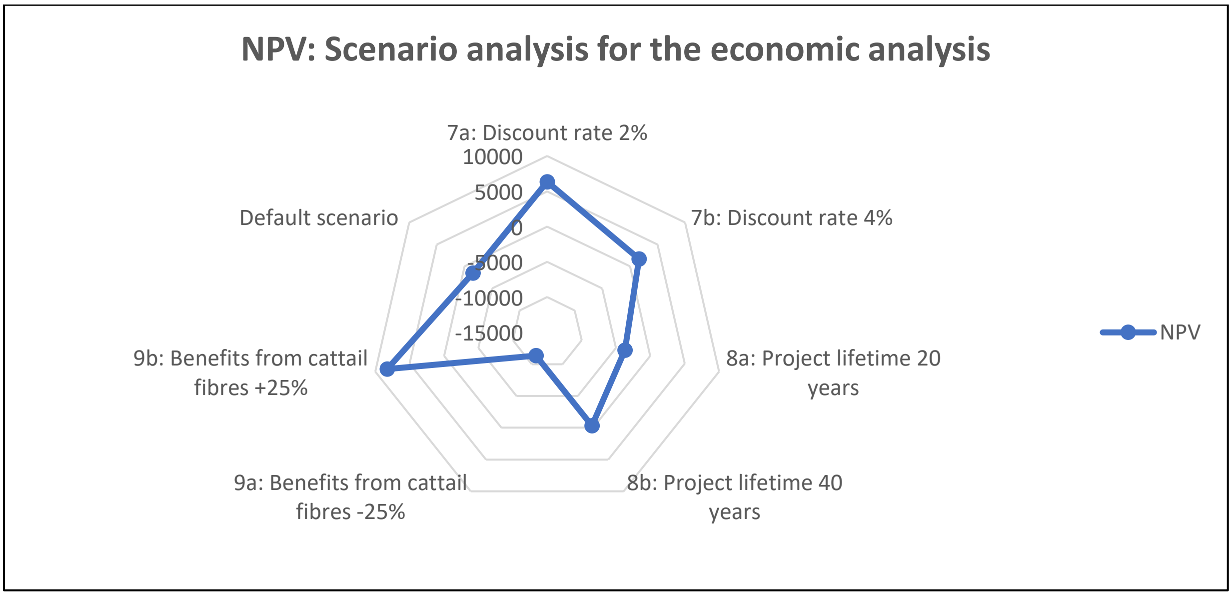

Figure 35: Results from the proposed sensitivity scenarios (cost-benefits) relative to the default values. Detailed data is added in Appendix 9.

The scenario analysis for the NPV reveals that the business case is mostly affected by variations in the benefits from cattail fibres. This analysis shows that a (small) adjustment of these benefits strongly affects the business case and that further elaboration on the benefits is required. Additionally, it can be said that next to the benefits, the assumptions for the project lifetime and discount rate are rather important for the business case. A decrease of the discount rate has a positive effect on the NPV, with almost more than triple NPV compared to reference NPV. Cheaper loans can thus result in higher viability, which is interesting to consider when discussing financing these projects by e.g. government or regional water authorities. Lastly, increasing the project lifetime to 40 years still results in a negative NPV. Decreasing the project lifetime to years, results in a further decline of the reference NPV.

Some key parameters are important in the LCA and NPV. For the LCA, these are the reference insulation material, the end-of-life and the yield of milk. The NPV is mainly affected by fluctuating benefits, followed by a different discount rate.

9.2 Limitations and recommendations for further research

There are some limitations within this research concerning the system boundaries, methodology and input data and their influence on the outcomes. The major limitations and associated ideas for follow-up research are explained in this paragraph, divided in system boundaries (set-aside land), LCA and GHGs from peatlands and the economic analysis. The chosen limitations explained here are considered as the main ones, or the ones which need further discussion, but there might be more interesting aspects to consider in further research.

9.2.1 System boundaries: Impact and related GHGs of set-aside land

It is assumed that sufficient land is available for this dairy farming on set-aside land. However, recent developments show a rise in competition for farmland globally, mainly due to urbanisation (Van der Zanden et al. 2017). On the other side, there is an increasing trend of agricultural abandonment since the 1950s, with agricultural abandonment as one of the dominant land use change processes in Europe (Van der Zanden et al. 2017). Agricultural abandonment is defined as a situation where control over land (e.g. agriculture, forestry) is given up and the land is left to nature. This might seem contrasting to the required increase of agricultural production, but, as stated by Van der Zanden et al. (2017), it is often closely related to intensified land uses in more suitable areas. The EU (2018) estimated that in the period 2015-2030 about 11% (equal to more than 20 million ha) of agricultural land in the EU are under high potential risk of abandonment. This is due to factors related to biophysical land suitability, farm structure and agricultural viability (EU, 2018). Spain and Poland are likely to face the greatest agricultural land abandonment. Though, these less productive areas, often related to soil erosion or unfavourable climatic conditions for agriculture (EU, 2018), could possibly be used for extensive dairy farming. Further research on the spatial aspects of the system change could be follow-up research.

9.2.2 Method and input data LCA: GHGs from peatlands and biogenic storage

A limitation to consider is the accuracy of the GHG-emissions from peatlands. Whereas an uncertainty factor (10%) is used to counteract some of the possible inaccuracies in the model and to counteract overestimation, data regarding the GHGs should be handled with care. One of the first mentioned aspects by M. Hefting (personal communication, February 14, 2020), expert in carbon and nitrogen cycles and interactions between plants and soils, is that measuring emissions from peatlands is highly sensitive due to chamber measurements. Even a small modification in circumstances, as e.g. soil shaking, could result in inaccurate or non-representable measurements.

Moreover, for simplicity, a Dutch peat layer with equal peat soil properties is assumed. Thereby neglecting differences in peat types (e.g. fens and bogs, clay, or sand on a (deep) peat soil) at different locations and therefore different responses to a higher water level and related GHGs. However, a previous research of Brouns (2018, p. 144) reveals that there is a difference in decomposition rates between fens (mostly West-Netherlands) and bog (North-Netherlands) peat, with faster decomposition rates in fen than in bog peat due to different soil characteristics and enzymes. This difference in decomposition rates could affect related GHG emissions, so differentiating in peat types could be a valuable follow-up research.

Lastly, the impact of climate change has been neglected in this research. However, previous research from Querner et al. (2012) and Zauft, Fell, Glaser, Rosskopf & Zeitz (2010) indicate that due to increase in temperature and the increased likelihood of summer droughts will enhance (secondary) peat decomposition. In the same line, it is assumed that the water level is kept stable, and no periods of (intense) summer occur. Nevertheless, the research of Brouns (2018) revealed that even short-term oxygenation of one-week could result in significant carbon losses. Dry periods could result in cracks in the soil, which can function as a chimney for O_2, resulting in more NO_2 and CH_4-emissions. An interesting research to highlight regarding this problem is adding small amount of clay as soil improver. The clay particles could rinse into the soil, fills up the pores in the cracks and prevents O_2 from penetrating in the soil (M. Hefting, personal communication, February 14, 2020). Moreover, literature by Van Agtmaal, Deru & Lenssink (2019) shows an extra advantage of adding clay. The clay particles ensure that the OM and nutrients are bound more firmly, which inhibits peat breakdown and land subsidence.

This shows that, despite the gradual built up of knowledge about land subsidence, more in-depth and accurate knowledge is still needed to increase uniformity and understanding regarding GHG emission from peatland ecosystems. This is confirmed by Van den Born et al. (2016) who states that "*what seems to be missing is a structured measurement and monitoring of the subsidence, as well as reliable modelling of processes that cause this subsidence*" (p. 25). Further research should therefore focus on the GHG-reduction of peatlands. It is revealed that in two of the three researched alternative systems (AS1 and AS2), most avoided GHGs emissions could be attributed to rewetting the peatlands, which shows the relevance of the subsystem in the system change.

The chosen methodology for considering biogenic storage is the PAS2050-methodology. This is an often-used method but this method also has its caveats, as previously explained in Section 2.2.2. An thorough understanding of the fate of the product is needed, and the assessment period of 100 years is sometimes be seen as rather arbitrary. Biogenic storage is seen as one of the main advantages of natural insulation, and it would be interesting to consider other methodologies as the dynamic method of Levasseur et al. (2013, in Wijnants et al., 2019) or the method of Vögtlander et al. (2014) based on the global carbon cycle and land-use change.

9.2.3 Method and input data: Economic analysis

Regarding the economic analysis, there are a few issues which should be considered. First, the cost analysis is speculative due to a lack of empirical data and little previous studies performed on the viability of paludiculture. The article of Wichmann (2017) is the most elaborated economic study of paludiculture, but this article focusses on reeds. In this research, it is tried to combine existing knowledge and to choose reference values based on well-thought assumptions. Though, this shows that more research is needed on wetland economics. This might contribute to adopting paludiculture in the future, as it is known that economic viability is one of the key drivers of (agricultural) system changes (Wichmann, 2017).

Secondly, it is assumed that main driver is the economic performance for the proposed land use change and adopting paludiculture. However, other factors can influence the economic performance as personal preferences of farmers, long-term agreements with procurers of processing chains, previous investments in crop specific machinery and equipment and specific land use due to policy measures and subsidies (Van der Hilst et al., 2010).

Furthermore, the economic analysis has been performed on a small scale, which is here based on a one-hectare comparison between Dutch dairy farming and cattail-based paludiculture. Though, the change needs to consider the whole farm (business) and related individual (economic) subsystems. The presented NPV shows an economic picture of the relative profitability of paludiculture, but it does not represent every individual farmer's perspective. The proposed economic analysis could serve as a starting point on a smaller, perhaps regional, scale. Nevertheless, upscaling could also benefit from economies of scale, which can reduce total costs. It is expected that this mainly affects the fixed machinery costs.

Additionally, the chosen point of view for the commercial viability is limited. Firstly, the analysis has been performed through the farmers' perspective and their related yearly net income and NPV. For example, the extra revenues from valuing the GHG emissions from rewetting the peatlands by carbon credits are fully assigned to the farmer. In the current analysis, this provides no benefit for the producer nor the consumer in for example (a part of) revenues from carbon credits or a discount, whereas their commitment is needed for developing a (economic) sustainable product and supply chain. Integrating carbon credits for the biogenic storage or dividing the additional revenues from rewetting the peatlands might encourage these actors. Cooperation between the chain parties is of great importance in supply chain management. Further research could thus focus on chain analysis with a more balanced supply and demand-chain management, as the current analysis is more supply-chain focussed.

Another aspect is that it is assumed that the one-hectare is completely assigned to growing cattail for bio-insulation purposes. This might be optimal from a climate perspective, but growing cattail for one purpose can result in a limited added value, which gives a limited economic business case. For example, not only insulation material can be produced, but construction material as cattail-reinforced concrete could also be produced. This could raise awareness of cattail and their opportunities and enhances overall awareness and acceptance in the market.

Another interesting option could be the use of (a small percentage of) cattail for bio-energy. For insulation, cattail should be harvested at its driest. Burning a part of these dry cattail chips could generate energy, with a calorific value of cattail of 18.2 MJ kg^{-1} (Bestman et al., 2019).

Moreover, the research of Van Duursen & Nieuwenhuijs (2016) states that cattail has, in addition to the already known more low-value applications as insulation/construction material, some high-quality components which can be extracted and be used in pharmaceutical, nutraceutical and agrochemical industries. For example, the use of *Typpha* pollen and the use of these pollen as medicinal extract could enhance blood clotting. However, the literature research from Van Duursen & Nieuwenhuijs (2016) also states that there are still a lot of uncertainties within this field and further research is needed, which involve thorough patent-based research.

Elaborating on the economic viability, and preferably including empirical data could be valuable follow-up research to give a more realistic and accurate analysis. Additionally, a further research could for example focussing in improving the business case, thereby possibly combing low-and high-value applications of cattail. For example, a small percentage (1-5%) of the proposed yield could be assigned to high-value applications or using cattail for bio-energy, which might increase the business case.

9.2.4. Excluded categories in both the LCA and economic analysis

There are some categories which have not yet been considered, for example the costs and energy for the increased water level (fixation), other economic drivers as subsidies and valuing the other ecosystem services of peatlands. These categories are discussed in detail subsequently.

The water costs for current drainage or water elevation are excluded, but it is expected that if the current policy continues, the burdens of the water boards will rise further because of peat subsidence (Van den Born et al., 2016). It is estimated that these costs are 200 million Euros over a period of 40 years (Van den Born et al., 2016). However, it is also expected that these extra costs will not be a strong driver when it comes to future decisions about the function, usage, and management on a larger scale. Nevertheless, there might be local situations where the costs might be a strong driver. Integrating water costs might be interesting for the local business cases, although research is needed concerning allocation the avoided costs/extra revenues between farmers and water boards.

In line, the needed energy for the current drainage is excluded in this research, despite a few attempts to gather (confidential) data. It could be expected that for the current drainage a significant amount of energy is needed, which is presumably fossil-related energy. Including this avoided energy and adding the used energy for maintaining water levels related to paludiculture might even result in a further decrease of the total GWP in the alternative systems as it is expected that less energy is needed. Nonetheless, expertise within this field of water management is lacking for me and needs a more thorough study on water management of drainage areas with related needed energy.

Within this analysis, valuing the GHGs emissions from rewetting the peatlands is done by implementing a carbon credit system. However, there are also other options which might trigger this system change and could give serve as an economic driver. Th effect of subsides was out of this scope for this research, but previous research of Geurts et al. (2019) confirms that subsidies for investments in paludiculture could potentially solve economic barriers for large-scale implementation.

Further, this research is executed from a climate's perspective. However, peatlands also support rich biological diversity (Minayeva, Yu, Bragg & Sirin, 2017). Peatlands might present limited species diversity but present a high incidence of unique species and diversity of ecosystem types at various scales (Minayeva et al., 2017). Possible drivers of peatland biodiversity loss are invasive aliespecies, forestry, climate change, habitat loss, but also over-exploitation for agriculture. From an ecological point of view, pristine peatlands should not be used for agricultural purposes, but should therefore be protected entirely with a focus on nature restoration or development. This might even result in a further reduction of GHG as the CO_2-uptake by the plant growth offsets the methane emissions and even peat accumulation could take place. The plants should not be harvested because this might lead to CO_2 through digestion of the plants. This is also shown in a previous research of Woestenburg (2009) (in Kwakernaak, Van den Akker, Veenendaal, Van Huissteden & Kroon, 2010) and the results are added in Figure 36. Polder Oukoop has a relatively deep draining an intensive agricultural management, polder Stein has a fluctuating water level and is more extensively used (meadow bird management). The Horstermeerpolder is a wet area without the removal of crops, which was returned to nature in 1990s. It can be concluded that the nature reserve (Horstermeer) captures more GHGs than emissions. It should be said that this capture of GHGs in such new nature reserves could reduce over a longer period.

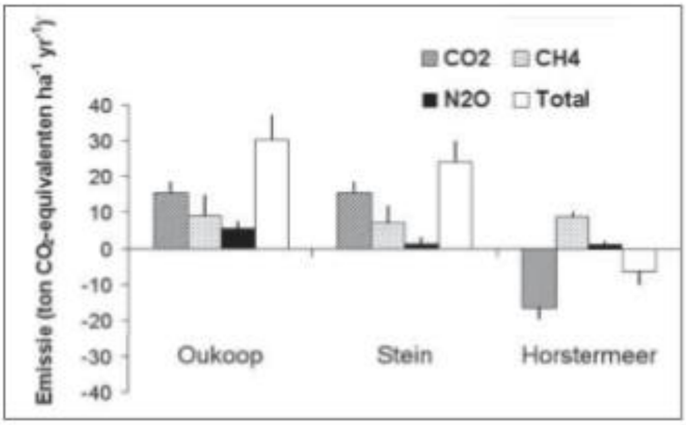

Figure 36: Measured emissions of GHGs in peatlands Oukoop (intensively used), Stein (extensively used) and Horstermeer (wet natural area). Emissions are measured on peatlands with a small top layer of clay (Kwakernaak et al.,2010).

However, paludiculture might be a second-best solution for areas where there is a high demand for productive (peat)lands. It can be a good combination of both restoration of nature and to provide a sustainable future for farmers. Currently, there is a nitrogen crisis in The Netherlands, which occurred after the Dutch Council of State ruled that the Dutch nitrogen policy Programma Aanpak Stikstof (PAS) conflicted with the European Habitat Directive. This resulted in a speed limit on roads, as well as a (temporary) stop on many construction projects. The agricultural sector also significantly contributes to nitrogen emissions and needs to act (Groenestein et al., 2019). Cutting the amount of livestock down by half might be a solution, but is rather unpopular by farmers. A solution as wet agriculture could be seen a chance to combine the goal of reducing nitrogen (and CO_2.eq) emissions by the agricultural sector and giving a prospect for Dutch farmers.

Related to water quality, paludiculture areas could serve as a buffer area between intensively used agricultural sites and protected areas. The introduction of these *wetland buffer zones* (WBL) might be beneficial for water regulation (Bestman et al., 2019). Wet crops can be used to purify nutrient-rich water, coming from agricultural areas (leaching) and the *wetland buffer zone* can function as a helophyte water, thereby purifying water to a quality that is less harmless for the environment. Productive wet crops can absorb large amounts of nitrogen, phosphorus, and potassium, which are removed from the water at harvest (Bestman et al., 2019).

Summarising previous paragraphs, an integrated ecosystem analysis for peatlands could be a valuable further research. Valuing these different ecosystem services, as biodiversity or water quality, by for example a carbon credit system could be interesting. This might also be relevant for implementing the system change of paludiculture at a farmers' level. The study of Hansson et al. 2012) on Swedish farmers' perception on sustainable agricultural system changes states that from their perspective, the focus should be on valuing the different ecosystem services of peatlands to early-adapt this system change. Only highlight the GHGs reduction potential might not be enough. However, this research is done in Sweden, and elaborated Dutch stakeholder analysis has not been performed yet. Research is needed to identify if Dutch famers have the same perception.

10. Conclusion

In this research, the environmental potential and economic viability of Dutch paludiculture-produced bio-insulation material from cattail has been assessed. The results have been compared to current agricultural land use on peatlands, which is dairy farming. This study combines several recent developments and emerging problems. These are an increased pressure for the agricultural sector to become more sustainable, more sustainable insulation material and counteract Dutch land subsidence and related GHGs. Paludiculture is proposed as a solution to counteract these developments.

Reflecting on the first sub question (SQ1), the optimal use of peatlands from a climate's perspective is paludiculture over dairy farming. The climate impact of cattail insulation plates gives a GWP of 2.78 kg CO_2.eq/f.u.$_{insulation}$ (without biogenic C) and 1.29 kg CO_2.eq/f.u.$_{insulation}$ (with biogenic C, PAS2050). In terms of GWP, substituting wool insulation (3.44 kg CO_2.eq/f.u.$_{insulation}$) by cattail insulation is therefore in favour of cattail plates. The GHG reduction potential from rewetting peatlands is high, ranging from an average reduction of 9.6 t CO_2.eq ha^{-1} yr^{-1} in West-Netherlands to 20.6-28.6 t CO_2.eq ha^{-1} yr^{-1} in North Netherlands.
Combining these results, a system change from dairy farming with current drainage to a water level associated with cattail-based paludiculture results in a decrease in GWP/f.u. in West and in North-Netherlands. A minimum reduction of 27% can be achieved from switching from dairy farming with relatively low drainage towards paludiculture (West-Netherlands). This can increase with a system change reduction up to 76% from dairy farming with deep drainage towards paludiculture (North-Netherlands), both percentages excluding biogenic storage. Taken into account the biogenic storage results in a greater reduction of GWP/f.u., with approximately 7 t CO_2.eq stored in the cattail insulation plates. Changing the land use on current deeply drained peatlands (-90 to -100 cm below groundwater level) could result in achieving almost negative emissions.

In the analysis of the competitiveness of cattail production with current land use, the NPV and income calculations show that a system change towards paludiculture cannot compete with current Dutch dairy farming under present conditions and commodity prices. Most cost effective cattail production is located in North-Netherlands due to a lower land rent price. With the influence of a carbon credit system assigned to the avoided GHG emissions from rewetting the peatlands, paludiculture could compete with dairy farming. This requires a yearly carbon commodity price of ~€40 per t avoided CO_2.eq. To achieve a positive NPV and thus paludiculture being economically attractive, a price of ~€3 per t avoided CO_2.eq (project lifetime: 30 years) is needed.
However, as indicated in the discussion, there are uncertainties regarding the economic performance and therefore additional research is required. More in depth assessment is needed e.g. regarding yield levels and related prices and discount rates. Moreover, a combined production of advanced products from cattail feedstock could be more promising than insulation material alone in terms of economic performance. On top of this, the business case from the producers' or consumers' perspective needs more in depth assessment.

This research has provided insights in current land-use related GHGs from milk production and provided insights in the potential GHG-reduction potential of cattail-focussed paludiculture. Paludiculture cannot (yet) compete with dairy farming and the economic potential is currently low, although introducing carbon credits can increase this economic potential. Overall, this research has shown promising results related to GHG reduction and could be a first step towards a more sustainable agricultural future, while at the same time building on the biobased economy.

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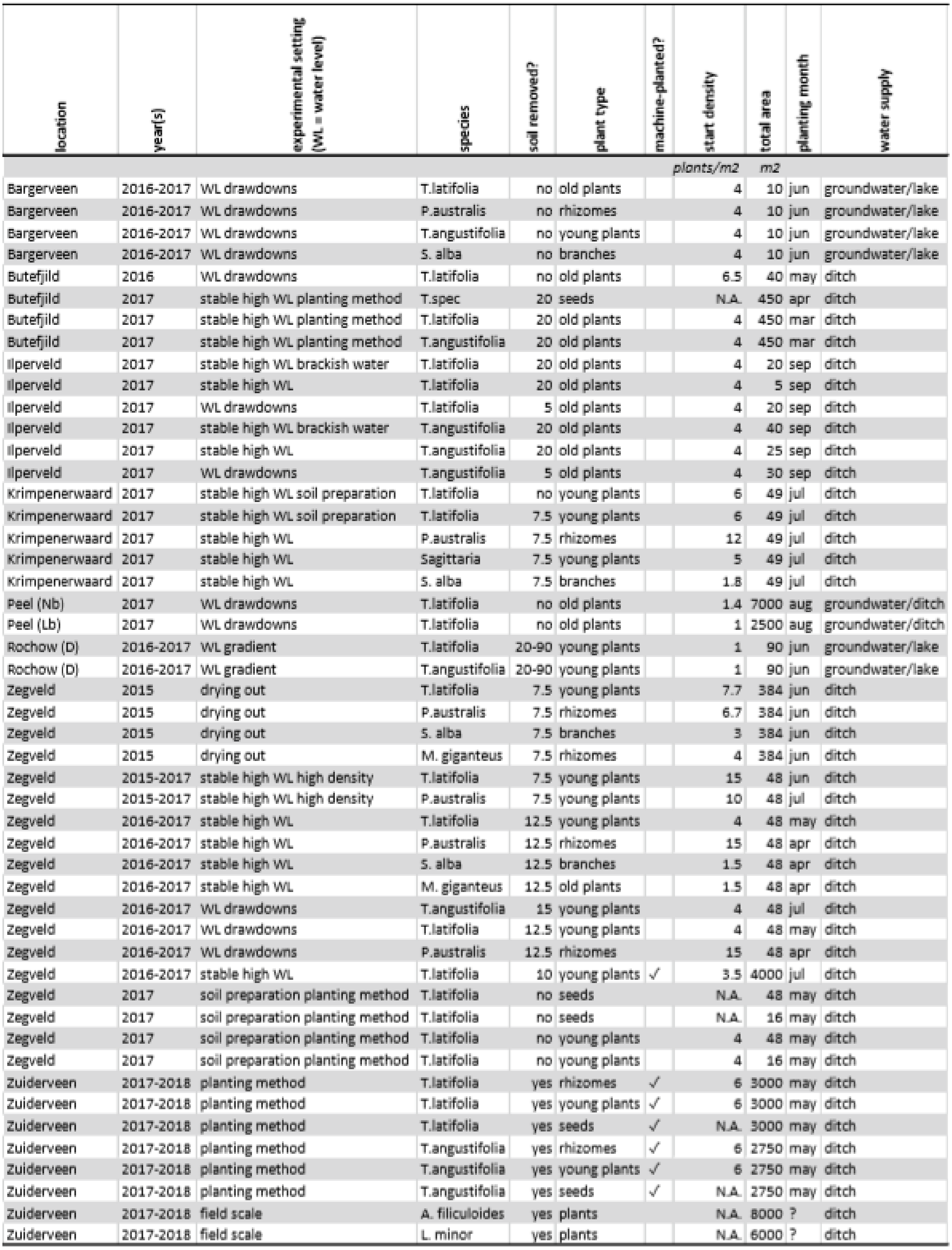
12. Appendix

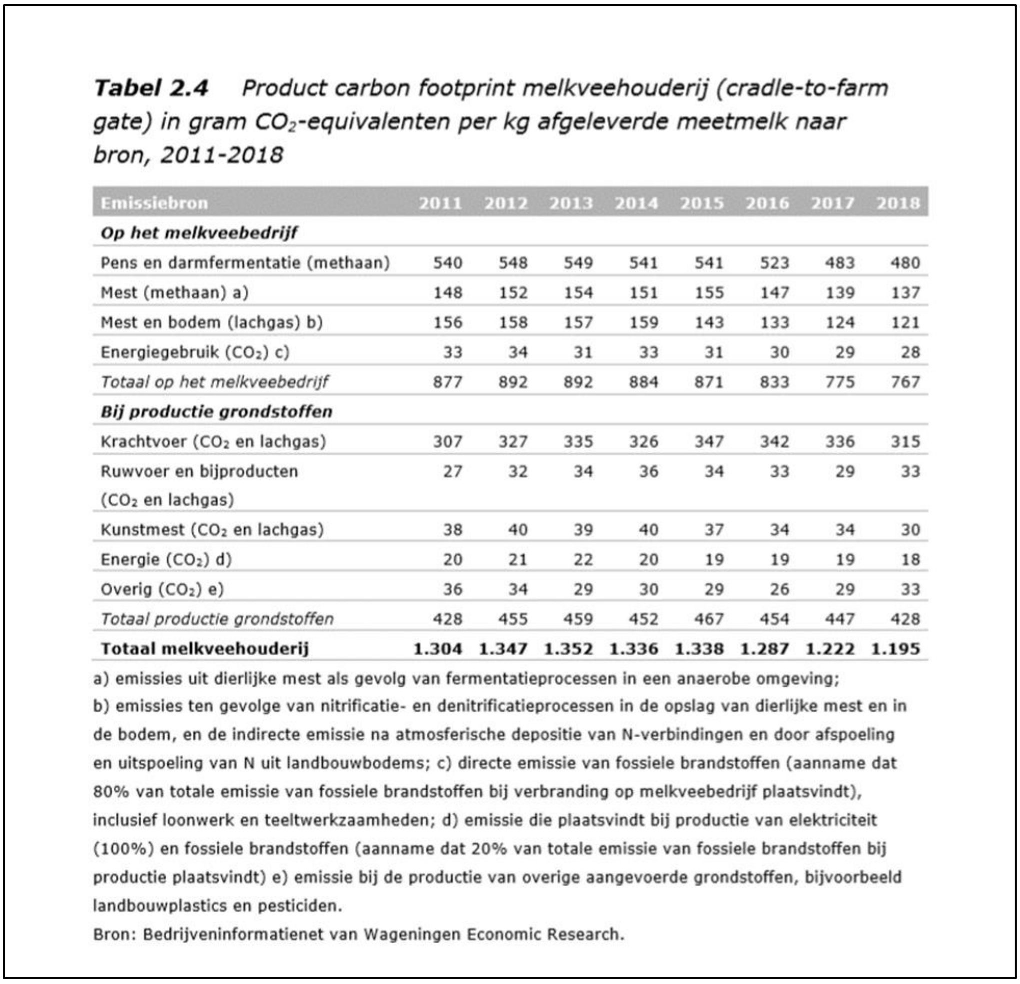
Appendix 1: Overview of existing and future paludiculture pilot projects, June 2018 (Geurts & Fritz, 2018).



location	year(s)	experimental setting (WL = water level)	species	soil removed?	plant type	machine-planted?	start density	total area	planting month	water supply
							plants/m2	m2		
Bargerveen	2016-2017	WL drawdowns	T.latifolia	no	old plants		4	10	jun	groundwater/lake
Bargerveen	2016-2017	WL drawdowns	P.australis	no	rhizomes		4	10	jun	groundwater/lake
Bargerveen	2016-2017	WL drawdowns	T.angustifolia	no	young plants		4	10	jun	groundwater/lake
Bargerveen	2016-2017	WL drawdowns	S. alba	no	branches		4	10	jun	groundwater/lake
Butefjild	2016	WL drawdowns	T.latifolia	no	old plants		6.5	40	may	ditch
Butefjild	2017	stable high WL planting method	T.spec	20	seeds		N.A.	450	apr	ditch
Butefjild	2017	stable high WL planting method	T.latifolia	20	old plants		4	450	mar	ditch
Butefjild	2017	stable high WL planting method	T.angustifolia	20	old plants		4	450	mar	ditch
Ilperveld	2017	stable high WL brackish water	T.latifolia	20	old plants		4	20	sep	ditch
Ilperveld	2017	stable high WL	T.latifolia	20	old plants		4	5	sep	ditch
Ilperveld	2017	WL drawdowns	T.latifolia	5	old plants		4	20	sep	ditch
Ilperveld	2017	stable high WL brackish water	T.angustifolia	20	old plants		4	40	sep	ditch
Ilperveld	2017	stable high WL	T.angustifolia	20	old plants		4	25	sep	ditch
Ilperveld	2017	WL drawdowns	T.angustifolia	5	old plants		4	30	sep	ditch
Krimpenerwaard	2017	stable high WL soil preparation	T.latifolia	no	young plants		6	49	jul	ditch
Krimpenerwaard	2017	stable high WL soil preparation	T.latifolia	7.5	young plants		6	49	jul	ditch
Krimpenerwaard	2017	stable high WL	P.australis	7.5	rhizomes		12	49	jul	ditch
Krimpenerwaard	2017	stable high WL	Sagittaria	7.5	young plants		5	49	jul	ditch
Krimpenerwaard	2017	stable high WL	S. alba	7.5	branches		1.8	49	jul	ditch
Peel (Nb)	2017	WL drawdowns	T.latifolia	no	old plants		1.4	7000	aug	groundwater/ditch
Peel (Lb)	2017	WL drawdowns	T.latifolia	no	old plants		1	2500	aug	groundwater/ditch
Rochow (D)	2016-2017	WL gradient	T.latifolia	20-90	young plants		1	90	jun	groundwater/lake
Rochow (D)	2016-2017	WL gradient	T.angustifolia	20-90	young plants		1	90	jun	groundwater/lake
Zegveld	2015	drying out	T.latifolia	7.5	young plants		7.7	384	jun	ditch
Zegveld	2015	drying out	P.australis	7.5	rhizomes		6.7	384	jun	ditch
Zegveld	2015	drying out	S. alba	7.5	branches		3	384	jun	ditch
Zegveld	2015	drying out	M. giganteus	7.5	rhizomes		4	384	jun	ditch
Zegveld	2015-2017	stable high WL high density	T.latifolia	7.5	young plants		15	48	jun	ditch
Zegveld	2015-2017	stable high WL high density	P.australis	7.5	young plants		10	48	jul	ditch
Zegveld	2016-2017	stable high WL	T.latifolia	12.5	young plants		4	48	may	ditch
Zegveld	2016-2017	stable high WL	P.australis	12.5	rhizomes		15	48	apr	ditch
Zegveld	2016-2017	stable high WL	S. alba	12.5	branches		1.5	48	apr	ditch
Zegveld	2016-2017	stable high WL	M. giganteus	12.5	old plants		1.5	48	apr	ditch
Zegveld	2016-2017	WL drawdowns	T.angustifolia	15	young plants		4	48	jul	ditch
Zegveld	2016-2017	WL drawdowns	T.latifolia	12.5	young plants		4	48	may	ditch
Zegveld	2016-2017	WL drawdowns	P.australis	12.5	rhizomes		15	48	apr	ditch
Zegveld	2016-2017	stable high WL	T.latifolia	10	young plants	✓	3.5	4000	jul	ditch
Zegveld	2017	soil preparation planting method	T.latifolia	no	seeds		N.A.	48	may	ditch
Zegveld	2017	soil preparation planting method	T.latifolia	no	seeds		N.A.	16	may	ditch
Zegveld	2017	soil preparation planting method	T.latifolia	no	young plants		4	48	may	ditch
Zegveld	2017	soil preparation planting method	T.latifolia	no	young plants		4	16	may	ditch
Zuiderveen	2017-2018	planting method	T.latifolia	yes	rhizomes	✓	6	3000	may	ditch
Zuiderveen	2017-2018	planting method	T.latifolia	yes	young plants	✓	6	3000	may	ditch
Zuiderveen	2017-2018	planting method	T.latifolia	yes	seeds	✓	N.A.	3000	may	ditch
Zuiderveen	2017-2018	planting method	T.angustifolia	yes	rhizomes	✓	6	2750	may	ditch
Zuiderveen	2017-2018	planting method	T.angustifolia	yes	young plants	✓	6	2750	may	ditch
Zuiderveen	2017-2018	planting method	T.angustifolia	yes	seeds	✓	N.A.	2750	may	ditch
Zuiderveen	2017-2018	field scale	A. filiculoides	yes	plants		N.A.	8000	?	ditch
Zuiderveen	2017-2018	field scale	L. minor	yes	plants		N.A.	6000	?	ditch

Figure 33: Overview of existing and future paludiculture projects.

Appendix 2: Carbon footprint of Dutch dairy farms, 2011-2017 (Doornewaard et al., 2017)



Tabel 2.4 *Product carbon footprint melkveehouderij (cradle-to-farm gate) in gram CO_2-equivalenten per kg afgeleverde meetmelk naar bron, 2011-2018*

Emissiebron	2011	2012	2013	2014	2015	2016	2017	2018
Op het melkveebedrijf								
Pens en darmfermentatie (methaan)	540	548	549	541	541	523	483	480
Mest (methaan) a)	148	152	154	151	155	147	139	137
Mest en bodem (lachgas) b)	156	158	157	159	143	133	124	121
Energiegebruik (CO_2) c)	33	34	31	33	31	30	29	28
Totaal op het melkveebedrijf	877	892	892	884	871	833	775	767
Bij productie grondstoffen								
Krachtvoer (CO_2 en lachgas)	307	327	335	326	347	342	336	315
Ruwvoer en bijproducten (CO_2 en lachgas)	27	32	34	36	34	33	29	33
Kunstmest (CO_2 en lachgas)	38	40	39	40	37	34	34	30
Energie (CO_2) d)	20	21	22	20	19	19	19	18
Overig (CO_2) e)	36	34	29	30	29	26	29	33
Totaal productie grondstoffen	428	455	459	452	467	454	447	428
Totaal melkveehouderij	**1.304**	**1.347**	**1.352**	**1.336**	**1.338**	**1.287**	**1.222**	**1.195**

a) emissies uit dierlijke mest als gevolg van fermentatieprocessen in een anaerobe omgeving;
b) emissies ten gevolge van nitrificatie- en denitrificatieprocessen in de opslag van dierlijke mest en in de bodem, en de indirecte emissie na atmosferische depositie van N-verbindingen en door afspoeling en uitspoeling van N uit landbouwbodems; c) directe emissie van fossiele brandstoffen (aanname dat 80% van totale emissie van fossiele brandstoffen bij verbranding op melkveebedrijf plaatsvindt), inclusief loonwerk en teeltwerkzaamheden; d) emissie die plaatsvindt bij productie van elektriciteit (100%) en fossiele brandstoffen (aanname dat 20% van totale emissie van fossiele brandstoffen bij productie plaatsvindt) e) emissie bij de productie van overige aangevoerde grondstoffen, bijvoorbeeld landbouwplastics en pesticiden.

Bron: Bedrijveninformatienet van Wageningen Economic Research.

Figure 34: Carbon footprint of Dutch dairy farming for the years 2017-2018 (Doornewaard et al.,2017). An allocation procedure of 85% for milk production and 15% meat is applied, cradle-to-farm.

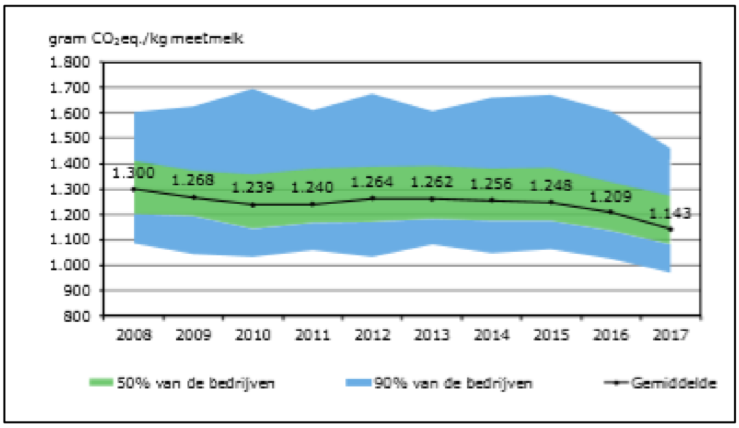


Figure 35: Spread of the carbon footprint within the consulted LCA of Dutch dairy farms (Doornewaard et al., 2017).

Appendix 3: Relative contribution of world regions to milk production and GHG emissions associated to milk production, processing and transportation (FAO, 2010).

The FAO performed an LCA-study to quantify the main sources of GHG emissions from the world's dairy cattle sector. It does not only assess the estimates of GHG emissions for major dairy cattle products and related services but is also estimates these GHG for main world regions and agro-ecological zones. The functional unit is 1 kg of Fat and Protein Corrected Milk (FPCM) raw milk from dairy farms and the FPCM correction is made for a conversion to a 4.0% fat and 3.3% true protein content. The consulted LCA has a *cradle-to-farm* gate approach, which is specified as: *all upstream processes in livestock production up to the point where the animals or products leave the farm, i.e. production of farm inputs, and dairy farming* (FAO, 2010).

The GHG emissions within the *cradle-to-farm* gate are the following (FAO, 2010):

- Processes for producing grass, feed crops, crop residues, by- products, and concentrates, including:
    - production of N fertilizer (CO_2);
    - application of manure and chemical fertilizers to crops, accounting for both direct and indirect emissions (N_2O);
    - deposition of manure and urine on pasture crops, accounting for both direct and indirect emissions (N_2O);
    - energy used for fertilization, field operations, drying, processing of feed crops and fodder (CO_2);
    - processing of crops into by-products and concentrates;
    - transport of feed from the production site to the feeding site;
    - nitrogen (N) losses related to changes in carbon stocks (N_2O).
    - changes in carbon stocks because of land use change (mostly from deforestation) in the previous 20 years (IPCC, 2006)
- Enteric fermentation by ruminants (CH_4).
- Direct and indirect emissions from manure storage (CH_4 and N_2O).

The related land use change emissions in this research are related to the expansion of soybean production into forest, shrub land or pasture (deforestation). This requires three steps, which are assessing (1) the land use change emissions related to soybean production in its main cropping areas, (2) the share of the soybean in the animal rotations and (3) the origin of the soybean in each country, which is estimated by trade-flow data (FAO, 2010).

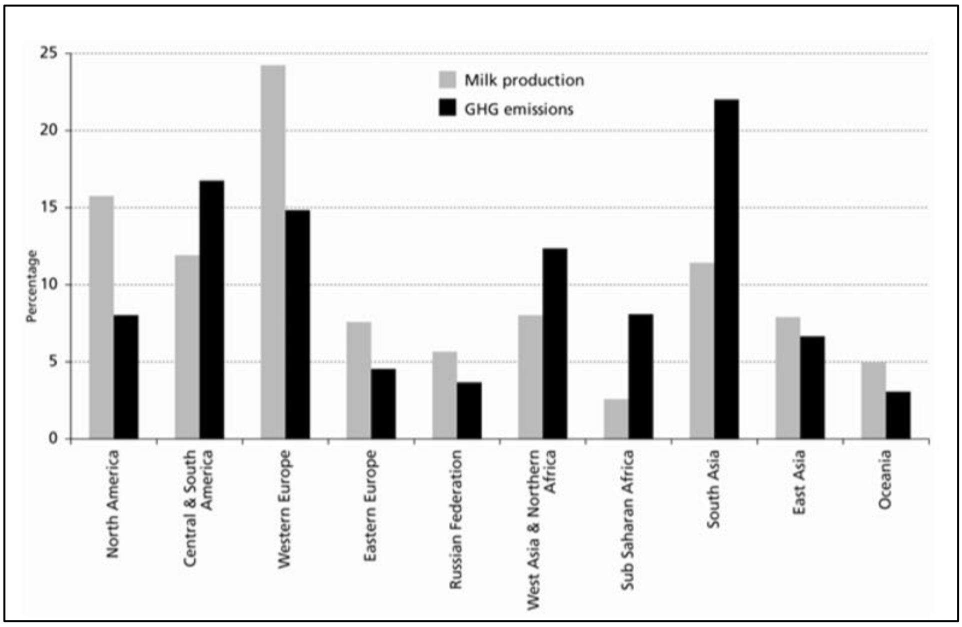


Figure 36: Relative contribution of milk production and related GHGs from different areas of the world (FAO, 2010).

Appendix 4: Production flows and related GHG emissions from glass and stone wool production (EcoInvent, cut-off criteria: 5%)

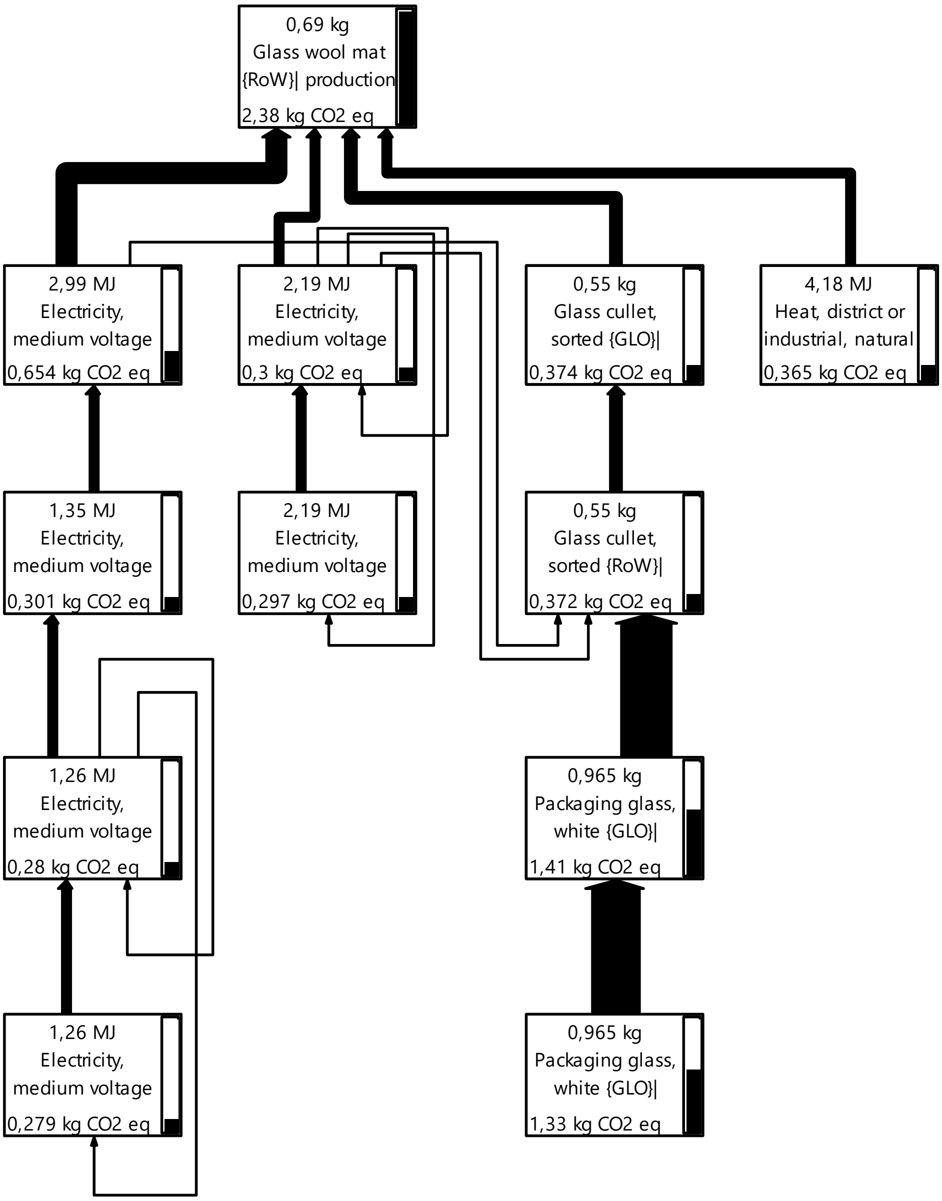


Figure 37: Production flows of a glass wool mat (EcoInvent, cut-off criteria 5%).

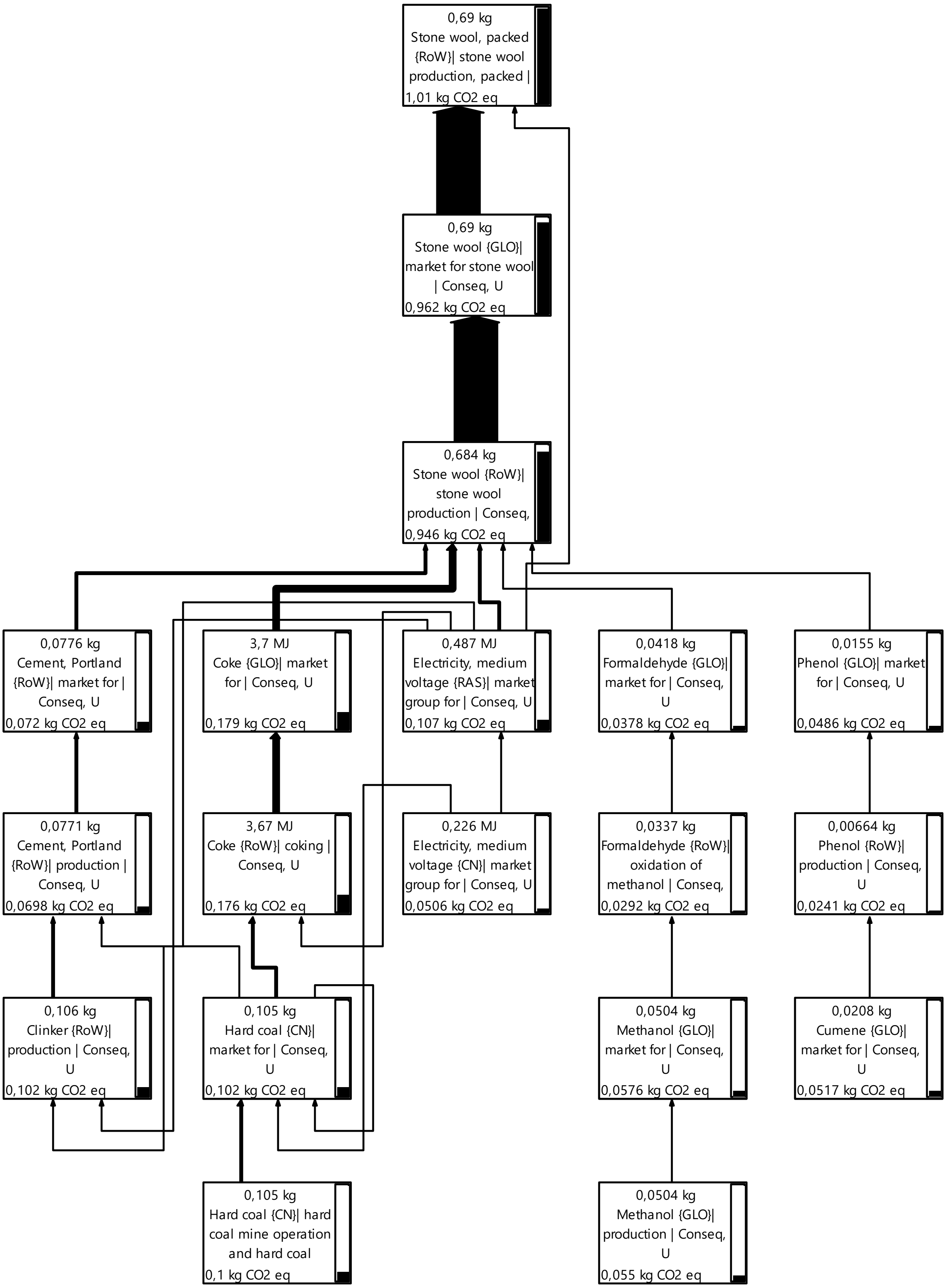


Figure 38: Production flows of a stone wool mat (EcoInvent, cut-off criteria 5%).

Appendix 5: Average income for Dutch dairy farms in the period 2001-2009 (Vogelzang & Blokland, 2011)

Table 29: Average net yearly income for Dutch dairy farms in the period 2001-2009 (Vogelzang & Blokzand, 2011).

	Euro per cow	**Euro per 100 kg milk**
Revenues	**3327**	**42.35**
Milk and other milk-products	2547	33.10
(pre-) Production process	232	2.88
Other revenues (e.g. recreation)	249	3.14
Subsidies	299	3.23
Costs	**965**	**12.09**
Forage	580	7.27
- ***Of which concentrates***	*412*	*5.21*
- ***Of which roughage***	*79*	*0.95*
- ***Of which moisture-rich feed***	*40*	*0.49*
- ***Of which rearing milk***	*30*	*0.38*
Animal health	85	1.05
Livestock improvement	68	0.83
Sowing seeds	27	0.34
Plant protection products	17	0.22
Fertilizers	82	1.04
Other allocated costs	105	1.34
Non-allocated costs	**1695**	**21.91**
Labour work	182	2.35
Other non-allocated costs	1513	19.56
Total	**667**	**8.35**

Appendix 6: Detailed data of the total GWP/f.u. in reference and alternative systems

Reference system

Table 30: System analysis of GHG emissions in reference system: dairy farming and insulation material.

CATEGORY	IMPACT	KG CO_2.EQ	QUANTITY		TOTAL GWP
Dairy farming on peatlands	1.23	kg CO_2.eq per kg milk	19264	milk ha^{-1}	23.7 t CO_2.eq
Glass/stone wool insulation	3.44	kg CO_2.eq per kg insulation material	178 4363	m^3 kg insulation	15.0 t CO_2.eq
Total impact f.u.					38.7 t CO_2.eq

Alternative system

For the alternative system, the carbon storage (below-ground and the biogenic carbon storage in the plates) is mentioned separately.

Table 31: System analysis of GHG emissions in alternative system: dairy farming and insulation material.

CATEGORY	IMPACT	KG CO_2.EQ	QUANTITY		TOTAL GWP
Dairy farming on set-aside land	1.29	kg CO_2.eq per kg milk	19264	milk ha^{-1}	24.9 t CO_2.eq
Cattail insulation	2.78	kg CO_2.eq per kg insulation material	178 4569	m^3 kg insulation	12.7 t CO_2.eq
Total impact f.u.				*Without biogenic carbon storage (ISO):*	37.6 t CO_2.eq
			Biogenic carbon storage:		6.8 t CO_2.eq ha^{-1}
Total impact f.u.				*With biogenic carbon storage (PAS2050):*	30.7 t CO_2.eq

Table 32: Detailed data of the total GWP/f.u. in the reference and alternative systems.

	REFERENCE SYSTEM			**ALTERNATIVE SYSTEM**			
TOTAL IMPACT F.U. (T CO2.EQ)	Dairy farming	23.7	t CO_2.eq	Dairy farming		24.9	t CO_2.eq
	Glass/stone wool	15.0	t CO_2.eq	Cattail insulation		12.7	t CO_2.eq
CO2-REDUCTION POTENTIAL*	-			-90 to -100 cm	28.6		t CO_2.eq
				-60 to -90 cm	17.0		t CO_2.eq
				-30 to -60 cm	9.6		t CO_2.eq
TOTAL GWP/F.U. (EXCL. CO_2 STORAGE)**		38.7	t CO_2.eq	-90 to -100 cm		9.0	t CO_2.eq
				-60 to -90 cm		17.0	t CO_2.eq
				-30 to -60 cm		28.0	t CO_2.eq

* CO_2 reduction potential is calculated by the difference between the current GHGs from peatlands in the corresponding drainage category to paludiculture water level (0 up to 20 cm), with a 10% uncertainty factor.

** Total GWP in system including biogenic carbon storage can be calculated by subtracting the CO_2-storage (6.8 t CO_2.eq/f.u.) from the Total GWP excluding CO_2-storage.

Appendix 7: Estimated yearly costs and benefits from cattail-based paludiculture

Table 33: Detailed data of the estimated yearly costs and benefits from cattail-based paludiculture.

		YEAR 1	**YEAR 2**	**YEAR 3**	**YEAR 4**	**YEAR 5-30**
		EU/ha	**EU/ha**	**EU/ha**	**EU/ha**	**EU/ha**
		Total				
BENEFITS	Selling the cattail fibres	0	850	1700	2550	3400
COSTS	Land costs					
	- North Netherlands	646	646	646	646	646
	- West Netherlands	796	796	796	796	796
	Field operation costs	42	376	376	376	752
	- Rhizome planting	34				
	- Fertilization	8	8	8	8	8
	- Harvesting	-	147	147	147	294
	- Windrowing	-	15	15	15	30
	- Baling	-	60	60	60	120
	- Transportation	-	146	146	146	292
	Labour costs	163	453	453	453	853
	- Rhizome planting	110				
	- Fertilization	53	53	53	53	53
	- Harvesting	-	244	244	244	488
	- Windrowing	-	66	66	66	132
	- Baling	-	50	50	50	100
	- Transportation	-	40	40	40	80
	Input costs	85	85	85	85	85
	- Fertilizers					
	Fixed costs	115	115	115	115	115
	- Fixed machinery costs					
ONE-TIME INVESTMENT	One-time investments	10300				
	- Soil preparation	7300				
	- Seeds/rhizomes	3000				

Appendix 8: Detailed data of the NPV for West and North-Netherlands with a carbon credit system

Table 34: Revenues from carbon credits (n =30 years) from the compliance and the voluntary market, North-Netherlands.

CARBON COMMODITY		**PROFITS FROM CARBON CREDITS (€ HA^{-1})**		
	Price (€/t)	Min	Max	Average
Compliance market	7	3066	5565	4326
Voluntary market				
- **Gold Standard**	10-20	6570	11925	9270
- **MoorFutures**	35-67	22338	40545	31518

Note: Average values for the prices of the carbon commodities at the voluntary market are used.

Table 35: Detailed data of the NPV in West and North-Netherlands, with and without a carbon credit system.

	West-Netherlands (WN)	**North-Netherlands (NN)**	**NN: Compliance market**	**NN: Gold Standard**	**NN: MoorFutures**
Benefits	93500	93500	93500	93500	93500
Land costs	-23880	-19380	-19380	-19380	-19380
Field operation costs	-444256	-44426	-44426	-44426	-44426
Input costs	-2550	-2550	-2550	-2550	-2550
Fixed costs	-3450	-3450	-3450	-3450	-3450
Investment costs	-10300	-10300	-10300,00	-10300,00	-10300
Carbon credits			4326	9270	31518
NPV value (€ ha^{-1})	-3599	-1534	2546	7211	28199

The assumed carbon commodity prices are 7, 15 and 51 € per ton avoided CO_2 for the compliance market, Gold Standard and MoorFutures respectively, as described in Table 17: Carbon prices at compliance and voluntary market.

Appendix 9: Detailed data for the sensitivity analysis

Table 36: Results of the sensitivity analysis for various scenarios, related to the performed LCA. Cells are empty if the scenario does not affect these parameters.

	DEFAULT SCENARIO	**1**	**2**	**3A (-25%)**	**3B (+25%)**	**4A**	**4B**	**5A (-25%)**	**5B (+25%)**
GWP/F.U.$_{\text{WOOL}}$ INSULATION	3.44					4.75	2.03		
GWP/F.U. IN RS	38.7			32.8	44.6	44.4	32.6		
GWP/F.U.$_{\text{CATTAIL}}$ INSULATION	2.78	2.70	2.21					2.48	3.08
GWP/F.U. IN AS (INCLUDING BIOGENIC C)	30.8	30.4		24.5	37.0			29.4	32.1
GWP/F.U. IN AS (EXCLUDING BIOGENIC C)	37.6		28.2						

Table 37: Results of the sensitivity analysis for various scenarios, related to the cost-benefit analysis.

SCENARIO	**DEFAULT SCENARIO**	**7A 2%**	**7B 4%**	**8A 20 years**	**8B 40 years**	**9A -25%**	**9B +25%**
NPV North-Netherlands (€ ha^{-1})	-1535	6349	1664	-3700	-319	-11340	8271