The replacement of maize (Zea mays L.) by cup plant (Silphium perfoliatum L.) as biogas substrate and its implications for the energy and material flows of a large biogas plant

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Abstract: Excessive cultivation of maize (Zea mays L.) as a biogas substrate has fired debate about potential land-use change effects of bioenergy cropping systems. Cup plant (Silphium perfoliatum L.) is a perennial biogas crop that provides more environmental services than maize. This study investigated (i) how to replace maize with cup plant as a biogas substrate in a large-scale biogas plant located in southwest Germany, and (ii) how to optimize the energy and material cycles of such a biogas plant given the new feedstock. The biogas plant produces 1000 m$^3$ biogas per hour with plans for it to be combined with a large dairy farm (1000 dairy units). It was found that the substitution of maize with cup plant as a biogas substrate results in a methane yield reduction of 10% to 20% due to lower biomass yields. However, there exists a strong potential to increase both biomass yields and biogas substrate quality of cup plant by optimizing establishment procedures and better genotypes. Furthermore, cup plant provides food and shelter for open land animals, including birds and insects, and could hence be a suitable alternative to maize for large biogas plants, being more environmentally beneficial. Extracting proteins from cup-plant biomass could also help replace soy with locally produced protein for feeding cattle. Hydrothermal carbonization is a promising tool for closing nutrient cycles and for extracting phosphate from digestate, but more research is needed before it can be put into practice. © 2020 The Authors. Biofuels, Bioproducts, and Biorefining published by Society of Chemical Industry and John Wiley & Sons, Ltd

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Introduction

The German term ‘Energiewende’, meaning ‘energy transition’, describes that country’s approach to achieving a more environmentally friendly and economically independent energy supply. The core of this transition consists of the substitution of fossil fuels with renewable energy sources. Today, renewables make up more than one-third of power production in Germany, making them the foremost source of energy in the country’s electricity supply. Other dominant energy sources such as lignite, hard coal, natural gas and nuclear power have been static or slowly decreasing in the past 20 years, but the share of renewable energy in the German energy landscape has been increasing continuously. The success of its rapid expansion lies in the introduction of the Renewable Energy Sources Act (EEG) by the German federal government in 2000. By guaranteeing fixed rates for the purchase of renewable energies, it has facilitated market access for emerging technologies that convert natural resources into a usable energy form. The Act has been revised on numerous occasions (EEG 2004, EEG 2009, EEG 2012, PV amendment 2012, EEG 2014, EEG 2017), and it has served as a framework for the development of renewable energy from niche applications to mainstream solutions in the power-generation sector.

Within the field of renewable energy, the individual energy-generation technologies contribute to gross German power production to different degrees. At around 17.5%, wind energy makes up almost half of the electricity generated from renewable resources (35.2%); biomass and solar energy both constitute around 7%. The most important elements of the energy transition therefore consist of the volatile renewables, wind power and solar energy. Long-term expansion scenarios estimate that by 2050, wind and solar power will provide about 80% of the country’s installed renewable power generation capacity and that it will thus come close to achieving the policy objective of decarbonizing the German electricity sector.

According to the Federal Network Agency, wind and solar power are dependent on weather conditions and consequently power generation is subject to fluctuations. In an energy system that is predominantly based on renewable energies, it is necessary to manage such large and rapid fluctuations while maintaining the flexibility to respond to variations in electricity demand. The provision of a basic energy supply and options for flexible power generation are thus necessary. Biogas production provides stable bioenergy generation and various scholars view bioenergy production from biomass as the most prudent current option to serve flexible consumption demands.

As part of the EEG, the German government has supported the countrywide development of biogas plants financially. Since the law came into force, the number of biogas plants in Germany has risen from 1050 in 2000 to almost 9500 in 2018, generating a total of almost 8000 MW in 2017. This accounts for around half of the total bioenergy produced from biomass in Europe. However, high feedstock costs and much lower production capacity have, over time, led to a less significant decrease in bioenergy generation costs in comparison to wind or solar power, which is why it remains more expensive.

Since the fundamental revision of the EEG in 2017, the market for biogas is now at a crossroads. The level of remuneration for renewable power is no longer fixed by the state but is determined by tender processes. This means that the funding of biogas plants in the scope of the EEG depends on successful participation in tendering procedures. Such tendering applies to newly constructed large plants >150 kW. Transition periods for exiting plants – such as the one operated by the Energiepark Hahnennest located in Southwest Germany (EPH) – are granted. Furthermore, the EEG 2017 limits the expansion volume of large biogas plants in favor of small-scale and manure-based plants. Accordingly, biogas plant operators like EPH are exposed to an increased competition and their financial stability is reduced due to uncertain offers and amounts in tendering. Furthermore, EPH faces public opposition due to the use of maize (Zea mays L.) as a biogas co-substrate. Notwithstanding the fact that maize cultivation – if conducted in accordance with good agricultural practices such as wide crop rotations, optimal fertilization management, and harvest determination – can have comparably low negative environmental impacts, the switch to more social-ecological cultivation systems, such as perennial cropping systems, can help biogas farms improve the public image of biogas production. This is because biogas production is increasingly associated with monotonous maize cultivation, and is thus associated with the problems of its cultivation. Maize cultivation (i) reduces pest suppression services by predatory insects, (ii) provides fewer ecosystem services than perennial biomass crops, (iii) is labor intensive compared with perennial biomass crops, and (iv) hardly adds any aesthetic value to the landscape.

The biogas plant as a hub in the sustainable bioeconomy

The current agricultural system is based on the use of mineral fertilizers for crop cultivation and high protein feed for livestock farming. The production and transportation of...
these minerals is, however, very resource intensive and the future availability of fossil-based mineral fertilizers remains unstable.\textsuperscript{62} One of the dominant protein sources in feed applications on the world market is so\textsuperscript{y},\textsuperscript{63} whose cultivation contributes significantly to the continuous deforestation of the Amazon.\textsuperscript{64–66} Sustainable agriculture must therefore focus on methods of nutrient recycling to reuse existing minerals and intensify the search for alternative protein sources with fewer negative environmental impacts. Current research ascribes strong potential to biogas plants in this context, considering them a central pillar of a sustainable bioeconomy.\textsuperscript{67} Their potential to serve as a biorefinery platform for integrated activities prior to and after the production of biogas is under investigation. Diverse substrate options for the fermenters are under discussion because of the capping of maize inputs at 47\% (mass based) with a future cap of 44\% from 2021 onward.\textsuperscript{34}

A promising alternative to maize as energy crop is cup plant (\textit{Silphium perfoliatum} \textit{L.}), which not only has similar properties in terms of biogas generation\textsuperscript{68–70} but stands out due to its ecological benefits such as soil protection and the provision of food for pollinators.\textsuperscript{71,72} Cup plant is compatible with the recent European law on advanced biofuels,\textsuperscript{5} and it was added to greening measures in 2018.\textsuperscript{73} Cup plant is discussed in greater detail below.

Another relevant topic is the concept of co-producing protein and energy from the same input material: silage. This concept further optimizes the energy and material flows at the EPH. Possible options for the extraction of proteins for animal feed from silage are discussed below. The residual biomass remains to serve as a substrate for the biogas production. The nutrient recovery from the digestate allows for an extraction of potassium (K), nitrogen (N), and phosphorus (P) from the nutrient-rich waste stream.\textsuperscript{74–78} The extraction of phosphates from the digestate produced at the EPH is introduced below.

Biogas production, as well as strengthening related biorefinery concepts, contributes to a reduced dependency on fossil resources for fuel and material use. It remains the overall motivation for this study to look for opportunities to optimize energy and material flows that return organic residues back to the public as energy, fuels and bio-based products.

Social-ecological considerations

Biogas production can be linked to many social-ecological benefits.\textsuperscript{22,79–83} The generation of biogas contributes to the German energy transition and the national aim of increasing the country’s share of renewable energy sources. Biogas use is CO\textsubscript{2} neutral because the substrate consists of biogenic material that has stored airborne CO\textsubscript{2}, while its digestate serves as organic fertilizer, returning organic material back to the soil.\textsuperscript{18} The carbon content of the soil is improved, and mineral fertilizer usage is reduced. Biogas therefore effectively closes the global carbon cycle and reduces greenhouse gas emissions, which are predominantly related to the combustion of fossil energies. The national energy supply can be strengthened and political dependence on oil-supplying countries can be decreased. The subsequent conversion of the generated biogas into methane gas also enables its use as a transportation fuel with a quality comparable to natural gas. Anaerobic digestion in biogas plants is also an effective mean of organic waste management. Moreover, the operation of decentralized biogas plants supports the creation of new jobs in rural areas and generates an additional source of income for local farmers,\textsuperscript{84} as in the case of the EPH. The choice of substrate can have positive impacts on the biodiversity and the landscape when, for instance, perennial or flowering crops are selected. These allow the valorization of by-products and waste streams and contribute to a circular economy.

In view of these considerations, this study will therefore focus on the following three research questions:

1. To what extent is biogas production impacted by an increase in cup plant as ensiled biogas substrate?
2. Which concrete options can be pursued in the search for alternative protein sources in dairy cattle feed and how feasible is their implementation?
3. How can biomass conversion processes contribute to a more efficient use of anaerobic digestate and the recycling of nutrients?

The approach includes a quantification of material flows at the EPH to the best of the authors’ knowledge. In the beginning, the current business cycles at the EPH are presented and quantified. Subsequently, the main focus is on the three optimization paths – cup plant (i), protein extraction (ii), and phosphate recovery (iii) – which have already partially been considered by the EPH. A discussion section follows, where the different benefits and challenges are again evaluated and their relevance for the EPH is highlighted. The authors’ recommendations constitute the final part of this study.

Material and methods – description of the biogas plant at EPH

The EPH is a consortium of four family farms that cooperated to build and run a large-scale biogas plant (Fig. 1) (47° 55’ 13.5° N, 9°19’ 17.3° E). Construction occurred in 2010, with the completion of the combined heat and power generator (CHP) in 2011, and the operation of the plant from 2012 until the present. Currently, the consortium collectively manages
Figure 1. Aerial view of the biogas plant at Energiepark Hahnennest: (1) storage of silage, (2) feeding unit, (3) fermenter 1, (4) fermenter 2 ((a) and (b) refer to two separate substrate lines), (5) biogas upgrading unit, and (6) storage of digestate.

Figure 2. Schematic overview of current energy and material cycles at Energiepark Hahnennest.

5930 pigs and 110 dairy cows, and ca. 763 ha of farmlands, 204 ha of grasslands, and 10 ha of forestlands, which is divided between the four farms. Figure 2 depicts the current material cycle that revolves around the crop cultivation and biogas generation carried out at EPH.

Animal production

Currently, the pigs and cows are managed independently at the respective farms of the EPH. Both the pigs and cattle are fed a mix of purchased feed that contains a large proportion...
of soybean as a protein source. Part of the manure generated by the livestock acts as feedstock for the fermenters.

**Crop cultivation**

The crop cultivation at the EPH is spread over a total land area of 1000 ha. This consists of 20% grasslands and 80% farmlands; 44% of the farmlands is cultivated with cup plant and the remaining 56% is used for maize cultivation. At the EPH, the centralized concept of biogas production is used. Following this concept, feedstock sourced from the surrounding area is delivered to a single central biogas plant connected to one centralized CHP unit. The farmlands managed by the farmers lie within a 5 km perimeter from the biogas plant, with minimal transport expenditure.

**Agricultural practice for maize**

Maize requires fertile soil with good drainage and for this reason areas with higher quality soil are used for maize cultivation.\(^5\) Seeding of maize is done at nine seeds m\(^{-2}\) to achieve a coverage of \(\sim6.5\) maize plants m\(^{-2}\). Maize is grown in rotation with other annual crops such as oilseed rape or grass in subsequent years to ease the soil burden and maintain soil quality. The system is non-irrigated, relying solely on natural precipitation. Crop protection is carried out to industry standards, with a high reliance on pesticides. The soil is treated initially with glyphosate as a method of weed control.

**Agricultural practice for cup plant**

Cup plant is much more robust than maize, as it more tolerant than maize of marginal land conditions such as adverse rooting conditions, wetness, and contaminated soil.\(^7,8\) It is cultivated from seed, sown to obtain at least four plants m\(^{-2}\), and is harvested each year from the second vegetation period onwards. Cup plant grows only as leaf rosettes during the first vegetation period; the leaf rosettes are not harvested and therefore provide no viable financial return.\(^7\) Cup plant requires very little crop management as there are few relevant pests and diseases. It requires much less pesticide after the first year of growth.\(^7\) Cup plant is strong enough to outcompete weeds and does not require any herbicide measures from the second vegetation period onwards.

Harvest time is a key period for achieving high biogas yields. At EPH, both cup plant and maize are harvested once a year during the same harvest period, within 2 weeks of each other. This is logistically advantageous because it enables the harvesting workload to be distributed, ensuring efficient harvesting as well as adequate time for both crops’ subsequent soil preparation and processing of harvested cup plant. Cup plant is harvested at the end of the flowering period and just before seed maturation during the month of September as this achieves the highest biogas yield due to high percentage of dry mass accumulated in the stem.\(^7\) The harvesting process is carried out using a forage harvester, which leaves 20 cm of residual stem on the ground to allow plant regrowth for the next harvest.

**Biomass storage through ensilaging**

Following the harvest of maize or cup plant, the fresh biomass then undergoes ensilaging. Ensilaging is the anaerobic preservation of fresh biomass feedstock through spontaneous lactic acid fermentation.\(^8\) Given that the harvest of maize and cup plant is annual, ensilaging ensures a constant supply of feedstock throughout the year without spoilage of the biomass, given that the silage is stored anaerobically.\(^8\) Ensilaged maize also produces a higher methane content than green maize because ensilaged maize contains higher amounts of acids and alcohols, both of which are important for methane production.\(^8\) The resulting silage is used as the main feedstock for the biogas fermenters. The ensiling area is 125 × 85 m with a filling height of 5.5 m. This corresponds to a capacity of about 58 400 m\(^3\) (or 300 Mg) of silage – adequate for a year’s storage of silage.

The EPH feedstock for the biogas fermenter consists of different types of fresh matter, including maize, cup plant, perennial ryegrass (Lolium perenne L.), mixed whole-crop cereals silage, apple pomace, and livestock manure. Both the manure and the apple pomace are added directly to feed the fermenters, whereas the plant matter is ensiled to improve its quality as a feedstock. The different materials are ensiled in alternating layers, with maize and cup plant making up the largest proportion. Livestock manure, mixed whole-crop cereals, and grass are obtained from the family farms’ livestock, farmlands, and cuttings from grasslands respectively. The apple pomace, consisting of mainly the skin, pulp, seeds, and stalk of the apple,\(^8\) is acquired for free, as it is a by-product from surrounding apple-juice producers. This material contains considerably higher concentrations of metals and sugars whose presence enhances methane formation at low concentrations.\(^9\) Although the proportion of the different components in the silage varies throughout the year, 95% of the fermenter substrate is hence internally sourced and produced from the farms. Silage is consumed at a rate of 200 Mg daily to feed the two lines of fermenters for biogas production.

**Application of digestate as fertilizer**

The majority of the NPK fertilizer required for maize and cup plant cultivation is provided by organic fertilizer in the form of digestate. The fertilizer, containing ammonium, phosphate, and potassium, provides nutrients to the soil...
while also replenishing the C content. This is the main form of fertilizer that farmers at EPH use for economic reasons in comparison with commercial fertilizers provided by companies such as BASF. Digestate is applied to both cup plant and maize, as well as to the grasslands. The utilization of the digestate in the fields and farmlands closes the nutrient cycle in the production of biogas as it feeds nutrients back into the soils used to produce the biomass. This is key for nutrient cycling, because it is carried out entirely at the facility. One of the largest costs in a centralized biogas system such as EPH is the feedstock supply and production; hence, the application of digestate back into the cultivation system also improves the economic performance of the EPH.

The digestate is a slurry composed of the liquid and solid fractions of the feedstock that remain undigested. As the production of methane from the feedstock removes C from the biomass, this results in a lowered carbon to nitrogen ratio (C:N). It allows the utilization of excess N from the solid phase that is unused by soil microorganisms by the plant through mineralization into NH₄⁺. Another benefit of using organic matter as fertilizer is the reduced level of NO₃⁻ leaching into the soil in comparison with mineral fertilizer. With regard to economic and environmental benefits, it is therefore in the interests of the farmer to reduce these losses by using as much organic fertilizer as possible. However, in keeping with the rules laid out in the Nitrates Directive implemented by the Fertilizer Ordinance in Germany in 2017, farmers must now comply to the EU common agricultural policy on organic N application of 170 kg ha⁻¹ and supplement the remaining requirements for N by using mineral fertilizer.

Despite the consistent use of digestate as fertilizer, the large quantities of biogas feedstock produce large amounts of digestate, which can be costly to store before its application onto the fields. Recently, the on-site digestate storage facilities at the EPH were expanded to a total capacity of 17 000 m³. The abundance of digestate could be a growing problem that, if left unaddressed, may lead to financial and logistical problems in future.

**Biogas plant components of the EPH**

In this section, the main components of the biogas plant of EPH are described. The main component of biogas plants is the digester (anaerobic digestion reactor tank), which is accompanied by several other components. At the EPH, two fermenters are combined as ring-in-ring containers. The outer ring serves as the main fermenter (F1), and the inner ring as a post-fermenter (F2). The F1 has a capacity of about 5000 m³, and the F2 holds 3500 m³. The total capacity of the storage fermenters is 17 000 m³. Twice a day, 45 Mg substrate is added into the fermenter. Cup plant takes longer to digest than maize or whole crop cereal silage, so the combination of two digesters in one line enables more efficient digestion of cup plant silage than using a single fermenter.

**Digestate storage**

In EPH the two digestate stores are designed as ring-in-ring containers and hold a total of 17 000 m³. The excess energy produced from the CHP is fed back into the fermenter in the form of heat and electricity.

**Combined heat and power plants (CHP)**

Combined heat and power generation is a standard utilization of biogas from anaerobic digestion in many countries with a developed biogas sector, as it is considered a very efficient utilization of biogas for energy production. Before the CHP conversion, biogas is drained and dried.

The two CHP units at EPH each consist of gas engines with an electrical output of 250 kW each. The combined heat and power plants are operated with raw gas and consume approximately 250 m³ per hour of methane. 500 kWh heat and electricity are produced by CHP at EPH. Many of the early generations of biogas plants have been established exclusively for electricity purposes, without consideration for the utilization of the produced heat. At EPH, the heat utilization is also considered a very important aspect of the plant economy. Generally, the sale of electricity alone is not enough to ensure economic sustainability, which is why biogas plants should also include heat utilization in the overall plant design. An engine-based CHP power plant has an efficiency of up to 90% and produces 35% electricity and 65% heat.

The EPH feeds two heating networks. The first is the Hahnnest heating network, with a total length of approximately 1700 m, providing heat to the village of Hahnnest. A second heating network, with a total length of approximately 1600 m, supplies the surrounding areas with heat.

**Biogas upgrading (biomethane production)**

Biogas can be distributed through the existing natural gas networks and used for the same purposes as natural gas or it can be compressed and used as a vehicle fuel. Prior to entering into the natural gas grid or to utilization as vehicle fuel, biogas must undergo an upgrading process, where all contaminants, and carbon dioxide, are removed, and the content of methane is increased from the usual 50%–75% to more than 95%. The upgraded biogas is often named biomethane. When removing carbon dioxide from
biogas, small amounts of methane (CH\(_4\)) are also removed. Methane has a stronger greenhouse gas effect than CO\(_2\) – i.e. a molecule of methane is 23 times more effective than a molecule of CO\(_2\) in trapping the radiated heat from the Earth.\(^8\) For environmental reasons, the minimization of methane losses is therefore important.\(^4\) At EPH, the gas-treatment plant works on the principle of a physical wash,\(^100,101\) in which the raw gas is refined to natural gas quality. Crude gas at EPH consists of the two main components CH\(_4\) and CO\(_2\).

**Biomethane grid injection and the gas pressure regulating and measuring system**

Upgraded biogas (biomethane) can be injected into and distributed through the natural gas grid after it has been compressed to the pipeline pressure. The amount of biomethane produced in EPH is determined in the measuring container of the gas feed system. Then the biomethane is fed into the gas high-pressure line of the terranets BW GmbH (Stuttgart, Germany) using two high-pressure compressors. The high-pressure line is located directly next to the biogas plant. As there is no gas storage facility at the EPH, all biomethane produced is fed directly into the pipeline. With the gas pressure regulating and measuring system plant, biomethane can be taken from the high-pressure line of the terranets BW GmbH. In this way it is possible to remove previously supplied gas at high energy consumption and store it during summer breaks.

**Peak load CHP**

The peak load combined heat and power plant consists of a gas engine with an electrical output of 200 kW, and it is switched on at peak consumption. It is independent of ongoing biogas production.

**Prospective future changes at EPH**

This section describes several approaches to the improvement of the flows of material and energy at EPH should the proposed nutrient recovery ideas be implemented, and how these new processes could be integrated into current activities (Fig. 3).

**Shift from maize to cup plant**

Today, maize is the main co-substrate for the biogas plant of the EPH but there is already a notable share of cup plant as biogas substrate. Cup plant has only recently been discovered as an energy crop for biogas production,\(^72,73,96,97,102–105\) and long-term data on its performance are still missing. The large-scale use of cup plant at EPH is somewhat unexplored. Hence, the next chapter aims at introducing the physiology of the cup plant, its ecological values, and its potential as a substrate for biogas production.

**Problems with maize**

In 2016, 48.9% of biogas plant substrates in Germany were energy crops (next to manure with 44.5% and waste with 4.2%). The input maize, at 76%, accounts for the largest share of those crops (FNR, 2019).\(^106\) However, this large-scale cultivation of silage maize is disadvantageous: As with other annual crops achieving a high yield, residents might complain about the change in natural scenery, biodiversity, and changed crop rotation patterns. Animal populations, pests, and diseases pose a high risk to the plants.\(^107,108\) Maize cultivation also decreases soil quality in that it is more prone to soil erosion and subsequently can cause the eutrophication of waterways and flooding.\(^109,110\)

As the public awareness on biodiversity especially in agriculture increases, the search for alternative substrates has intensified.\(^72\) One possibility is the cup plant. It is a perennial C3 plant originating in the temperate regions in North America.\(^111\) It belongs to the family Asteraceae,\(^102\) and takes its name from its cup-like leaves, which are arranged around the stem and trap water.\(^112\)

Cup plant is a neophyte in Europe; however, this argument can also be made for maize. Extensive cultivation of the cup plant could also lead to monocultures, which are generally linked to several ecological and agricultural disadvantages (see above). The next chapters put forward arguments why the cup plant is a more appropriate choice than maize.

**Comparison of cup plant and maize cultivation practices**

Optimum conditions for the germination of cup plants are given if temperatures vary over a longer period of time.\(^113–115\) In the first year, it grows small rosettes about 30 cm high and with 12–14 leaves.\(^111\) The plant also develops many horizontal side roots.\(^116,117\) During the second year, the stalks are formed from the vegetative buds that developed in the late phase of the first year,\(^116,117\) as soon as temperatures reach 5 °C.\(^113,117\) There are several stalks per plant and their number increases to up to 25 as the cup plant matures. The plant grows more than 2 m high (Fig. 4(a)).\(^118,119\) Between the beginning of July and the end of September, the cup plant produces large yellow flowers (Fig. 4(b)). New flower heads replace the old ones after ca. 11 days, allowing for a long flowering period.\(^118–120\) This is also a positive side effect for insects, especially pollinators, as they can feed on the
flower’s nectar and pollen for a long period of time.\textsuperscript{120,121} This is in contrast with many other energy crops, which do not flower for such long periods. This is therefore one of the cup plant’s biggest ecological advantages; the provision of food for insects and the resulting improved health of bees and other insects.\textsuperscript{117,122–124}

At the end of the flowering phase, the cup plant develops achene fruits. There are either 18–20 or 20–30 fruits per flower head and they are flat shaped and of a brownish color.\textsuperscript{118,125} Another advantage of the cup plant is its low soil and climatic requirements. The North American-native plant grows best in subcontinental climates,\textsuperscript{72} and at around 20 °C.\textsuperscript{111}
and is therefore already well adapted to European conditions. It prefers humus soil on deep-seated lands with a lot of moisture, e.g. along creeks and rivers. In general, different soil types did not show an obvious impact on the dry matter yield (DMY) of the cup plant but the higher the site of cultivation, the shorter the growing period and therefore the lower the yield. These low requirements regarding the soil make the plant suitable for many different locations across Europe.

Furthermore, the cup plant has a high water use efficiency and consequently is tolerant of drought conditions, although both drought tolerance and water use efficiency of cup plant are lower than for maize and alfalfa (Medicago sativa L.). This is due to its long roots. The cup-shaped leaves that are able to hold rainwater may prevent rain water in low precipitation events in the summer from reaching the ground, thus preventing the plant from using this water. The minimum water requirements resemble those of maize with 400–500 mm, but the cup plant can achieve higher biomass yields in arid years than maize.

Finally, the cultivation of cup plant can be a tool in the protection of soil, water and climate in general: The plant can be grown on marginal land and can be used to restore degraded land. It decreases soil erosion due to the long period that the soil is covered, in turn preventing nutrient leaching. It improves the fertility of the soil and its greenhouse gas balance due to carbon sequestration and enhanced soil formation.

The choice of the preceding crop does not have a large impact on the long-term yield because the cup plant can be used for ca. 15 years. However, it is best to cultivate a weed-suppressing crop, as weeds represent a strong competitive force during the first year of establishment. Recommended crops are maize, cereals, winter catch crops and root crops. Subsequently cereals can be planted.

As previously stated, weed growth can be problematic during the first year of cup plant cultivation. Thorough tilling is therefore necessary before sowing. Currently, most farmers plant seedlings of the cup plant as research on cup plant seed cultivation is lacking. Due to the predominantly low quality of seeds, the growth of the plants from seedlings is safer. However, the four farmer families running the EPH have invested much time and effort into the cultivation of quality cup plant seeds, which is why sowing is preferred at the EPH.

Sowing before the middle of May in Germany results in reduced development of the seedling. On the other hand, sowing later than the middle of June causes less ground coverage when the plants have completed their growth period. The development of the seedlings is also negatively impacted by cover crops. The highest biomass yields are achieved with spacing in the rows of 10 cm, and 50 cm the rows, sown at a depth of 1.5–2 cm. High-quality seeds can dramatically reduce the amount of seeds needed for optimum cultivation from 15–20 kg ha⁻¹ to 2–2.5 kg ha⁻¹. In general, much investment and time is required for the successful establishment of cup plant. Farmers can reduce initial costs from 5159 € ha⁻¹ to about 1950 € ha⁻¹ by switching from planting seedlings to sowing. This sowing, as a form of establishment, results in raw material costs of 129–138 € Mg⁻¹ (ODM) compared to 118–124 € Mg⁻¹ (ODM) raw material costs for the establishment of maize. The cup plant is therefore only marginally more expensive when farmers use quality seeds like those used at Hahennest. The seed-based cup plant propagation approach of EPH has been patented and thus may represent a lucrative side business in the future if more farmers switch from annual energy crops to the cup plant. For large farms that have access to the necessary machinery for sowing (cup plant and maize together), certified seed will very likely also be available in future, so that the complete package (seed, sowing and guarantee of success) will remain relevant for smaller farms. Cup plants may even prove to be more profitable in a life-cycle assessment, if ecological benefits are also considered. These benefits could be remunerated, for example, by a state-funded ‘public good bonus’.

The highest yields can be achieved with a mixture of mineral fertilizer and the digestate of the biogas plant. Fertilization should take place once, at the beginning of growth period, before the plants become too high. The most important limiting factor is nitrogen, which positively...
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Influences biomass yields. Here, studies show that 10 kg of nitrogen should be added to produce 1 ton of dry matter. During the first year of cultivation, 50 kg ha\(^{-1}\) and during the later years 130–160 kg ha\(^{-1}\) of nitrogen fertilizer are recommended. As always in crop cultivation, the available nutrients in the soil must be subtracted from the recommendations for fertilization. Hence, before fertilization with other nutrients, soil nutrient balances should be evaluated. For example, the cup plant absorbs about 250 kg ha\(^{-1}\) of potassium but only 30 kg ha\(^{-1}\) of phosphorus and 60 kg ha\(^{-1}\) of magnesium.

Lastly, weed management is crucial for cup plant cultivation, because the ground coverage is sparse and late during the first year. The cup plant also cannot be grown during the usage of any registered herbicide. So, weed removal and loosening the soil between the rows is necessary during the growing period. This extensive weed management is only necessary during the first year, as the perennial cup plant covers the soil quickly from the second year onward. The EPH optimized both the biomass yield and the weeding strategy in the first year of establishment by developing a seed-based establishment method for the cup plant. Moreover, methods of sowing cup plant under maize were developed. The intercropping of cup plant and maize during the first year of the cup plant establishment also promises to improve environmental performance of maize cultivation through decreased erosion and nutrient leaching.

Influence of the harvest time and ensilaging on properties of the cup plant

At the end of the flowering period, which is September in Germany, the cup plant is chopped by a forage harvester with DIRECT DISC system© and transported to the storage location to be ensilaged. Thus, it is harvested the same way and with the same equipment that is used for the maize harvest. This can lower investment costs for farmers looking to switch from maize to cup-plant cultivation. However, it is only possible to chop with the conventional maize extension system while the plants are upright. Since hail and wind damage occur in cup plant stands in summer, it is advisable to use a direct cutter bar. The crop can also be harvested twice: once in June and once in September. But as studies show, a single harvest achieves a higher yield than the two harvests combined. Furthermore the longer growing period increases the period in which insects can use the field for feed and as a habitat.

The DMY of the cup plant rivals those of conventional energy crops. While maize yields 14–21 Mg ha\(^{-1}\), cup plant reaches 11–17 Mg ha\(^{-1}\). This means that the DMYs are equal or about 20% lower for cup plant. However, it should again be noted that the rosettes in the first year provide extremely low yields. For this reason, only the biomass from subsequent years is used. The large variability in the achievable yield is due to several parameters affecting dry-matter content. The most influential is the date of the harvest. As expected, the yields were higher for later dates of harvesting, but there are conflicting studies about the consequences of a late harvest.

A late harvest is also preferable due to the higher dry matter content of the biomass. It should be at 260–300 g kg\(^{-1}\) to save weight for transportation and processing and because it guarantees a higher quality silage.

On the other hand, a later harvest time negatively influences the specific methane yield of the cup plant. As the plant grows, its chemical composition changes and the fiber content increases. The lignin that it contains is a poor substrate for the biogas process as it cannot be degraded under the anaerobic conditions in the biogas plant and hinders the degradation of cellulose. At the same time, the content of sugar that can be degraded and the protein content (proteins yield more methane than carbohydrates) actually decreases with time. This influence of the harvest time on the methane yield also holds true for maize.

To be able to feed biogas plants throughout the year, the energy crops are ensilaged. The cup-plant biomass shows a significant decrease in pH value during the ensilaging process. Large amounts of lactic acid are produced, preventing microbial decomposition of the biomass. The cup plant owes this to its high water-soluble carbohydrate content. The water content of cup plant is higher than in maize, in which water content of above 70% is usually associated with lower ensilage quality. For cup plant, however, it was shown at EPH that water content of 70%–75% did not result in larger amounts of waste water. Methods that increase the dry-matter content of the plant can therefore help to increase the quality of the substrate. Possibilities for increasing dry matter include wilting during harvest, the addition of extra carbohydrates or silage additives. The substrate also shows a higher quality when cup plant is ensilaged together with other crops such as maize, as it is currently done at EPH.

The most crucial property of the cup plant as a biogas plant substrate is its specific methane yield (SMY). Studies have shown that cup plant has a SMY of 0.232–0.275 m\(^3\) kg\(^{-1}\) volatile solids\(^{-1}\), which is lower than maize. It should be noted that pretreating similar substrates can increase their biogas yield and will also positively impact processing in the fermenter. With respect to cup plant, pretreatment effects...
on the biogas yield have not yet been studied.\textsuperscript{72} However, preliminary results from EPH showed that SMY can be increased to 300 m\textsubscript{N\textsuperscript{3}} kg\textsuperscript{-1} volatile solids\textsuperscript{-1}.

A better picture of the cup plant’s potential is given by the methane yield per ha\textsuperscript{96} because it also includes the biomass production per area and therefore ultimately, the cost of the methane.\textsuperscript{72,96} Here, studies show equal methane yield per ha for cup plant and tall wheatgrass (4301 m\textsuperscript{3} N ha\textsuperscript{-1}).\textsuperscript{96} Other studies found the cup plant yield to be around 2871–3828 m\textsuperscript{3} ha\textsuperscript{-1} which is 35% lower than the yield from maize.\textsuperscript{72,113} However, these studies are often based on a relatively small sample size. As the cup plant has only been studied as a biogas substrate in recent years, more data are needed.\textsuperscript{72}

Cup plant in the fermenter

During continuous anaerobic digestion, other substrates are decomposed faster than the cup plant.\textsuperscript{69,96,115} This means that the cup plant could have a higher biogas production than other substrates in the second fermenter ring but, again, more data are needed to reach a conclusion.\textsuperscript{72} The effect of the cup plant on the fermenter should also be considered. Other substrates with high fiber content similar to the cup plant form floating layers, and fibers cluster on the driving wheel.\textsuperscript{143} Mechanical and biological pretreatments could be used to counteract these problems.\textsuperscript{142}

The future of the cup plant at the EPH

The cup plant is an important part of the value chain of the EPH. The farmers plan to increase the farmland used for cup plant cultivation from 44% to 70% in the near future. Hence, it may represent a key variable in the optimization of their material and energy flows. The dry matter of the cup plant contains 9.8% crude protein. If this protein is extracted, it could be used as feed for the animals at the EPH. This possibility for optimization is described in detail below.

The cup plant also has different levels of methane yield from maize. The expansion in its cultivation will therefore affect the methane production, EPH’s most profitable output. Hence, a comparison of the current state and possible future production scenarios can highlight changes in the value chain. The mixed silage at the EPH currently consists of maize, cup plant, manure, grass, whole-crop silage and apple pomace, thereby producing 10 170 m\textsuperscript{3} CH\textsubscript{4} d\textsuperscript{-1}. If the fermenter were to be fed with 100% cup plant silage, this would hypothetically produce 38 025 m\textsuperscript{3} of methane per day. This would represent an increase in methane production of 73.3%. However, with the current cultivation of cup plant, such practices could only be sustained for 25 days a year. Even with an increased cultivation area, there would not be sufficient cup plant substrate for a whole year. The calculations for this scenario are shown in Table A1.

It therefore makes more sense to analyze the hypothetical the methane yield when 70% of the farmland is dedicated to cup plant cultivation instead of the currently 44%. In this scenario, it is assumed that the additional 26% of farmland is subtracted from the current maize cultivation area. The EPH has 763 ha of farmland, which would mean an additional 198.38 ha of cup plant. At an assumed DMY of maize of 17.5 Mg ha\textsuperscript{-1}, this results in 3471.7 Mg less maize per year. Then, 75% of maize would enter the methane production with an average SMY of 0.307 m\textsubscript{N\textsuperscript{3}} kg\textsuperscript{-1} volatile solids\textsuperscript{-1}. Hence, there would be 798 657 m\textsuperscript{3} less methane per year. At the same time, cup plant has an assumed DMY of 15 Mg ha\textsuperscript{-1} leading to an additional 2976 Mg yr\textsuperscript{-1} of cup plant. With an average SMY of 0.254 m\textsubscript{N\textsuperscript{3}} kg\textsuperscript{-1} volatile solids\textsuperscript{-1}, 75% of cup plant biomass can provide 56 562.2 m\textsuperscript{3} more methane per year. If this value is offset against the lost methane from maize, there would be 742 095 m\textsuperscript{3} less methane produced each year. This would mean a loss of 20% of the annual methane production for the EPH. Nevertheless, it should be noted that through optimized fertilization and harvest dating, the methane production of cup plant is between 0% and 10% lower than that of maize. This has been borne out by the experience of growers at EPH. There is, however, still no scientific evidence for this, which is why this study relied on the rather pessimistic data from the literature (cup plant generates ~20% of maize methane production). The corresponding calculations are shown in Table A2.

Potential developments in closing of material cycles

In the following chapter, we explore the ideas of closing material cycles through recovery of the nutrients N and P in the form of protein and phosphate respectively. The idea proposed by the EPH of extracting protein from currently used biomass is elaborated, providing possible extraction scenarios using prospective technology. Moreover, the novel concept of phosphate recovery from the digestate is proposed, giving a holistic overview of the process including the technical aspects of recovery.

Protein extraction from biogas substrate

Cup plant silage as a protein source

One possible method of decreasing the amount of soy-based protein, is the extraction of protein from biomass used as feedstock. Not only would this allow substitution of soy-based protein source in livestock feed, but extraction of N...
in the form of protein would also reduce the N content in the resulting digestate. Seeing the high potential of digestate accumulation, the reduction of the N concentration would allow a higher use rate, and therefore circumvent future costs in increasing digestate storage capacity. In light of this, the possible extraction of protein from cup plant feedstock, will be assessed. It was proposed by the EPH as an idea for further closing nutrient loops, considering that cup plant is projected to make up to 70% of the biogas substrate at EPH in the future.

There is contradictory data reported on the protein content of the cup plant, some showing protein content of the whole plant of ~7%, and others showing numbers in excess of 15%.\textsuperscript{117,138,144} This, in part is due to the small amount of research carried out on the cup plant and the implications in its use as an energy crop. However, the abundance of protein in the leaf compared to the stems, remains evident through the literature, where it is several times higher. Crude protein content in leaves reached 15%–17% at high N fertilization,\textsuperscript{138} making the cup plant a good potential candidate for protein extraction. However, this crude protein content is heavily dependent on harvest time and drops nearing the end of the growing season. Leaf protein concentrates (LPC) give a strong potential for further biomass utilization by co-production of protein and biogas feedstock.\textsuperscript{145}

**Extraction process**

The extraction of LPCs involves the separation of protein from cellulosic matter in the leaves. There are currently two main pathways of protein extraction from biomass available, namely mechanical based and aqueous extraction.\textsuperscript{145} Dale et al. describe four different means of feed protein co-production from these two processes in the context of energy crops. These include (i) the extraction of protein from fresh leaf material ‘juice’; (ii) recovery of protein from the solid press-cake fraction; (iii) solvent protein extraction from dry plant material; and (iv) high-protein residue recovery from the processing operations. In addition, (v) biological protein-extraction from cup plant with insect larvae was tested in a practical experiment to assess this option.\textsuperscript{146}

The first two methods, (i) and (ii), are directly involved with the mechanically based method, which requires the grinding and pressing of fresh biomass to obtain the press-cake residue (ii) and nutrient-rich juice (i), in which the protein coagulates and is subsequently fractionated.\textsuperscript{147} One drawback, however, is that the process requires fresh green biomass. In the case of EPH this poses potential problems, because fresh green biomass is only available during the yearly harvest time and would therefore limit the processing time to a few weeks in the year before the material is ensilaged. As the downstream digester substrate will also be derived from this process, it limits both the availability of the feedstock and therefore the feeding rate into the fermenter at the same time. The process becomes increasingly unfeasible when considering the amount of fresh biomass that requires processing immediately post-harvest from over 300 ha of cup plant cultivation at EPH. The maintenance of the quality of fresh biomass would require yet more investment to ensure the right conditions for the extraction process. In the light of this, aqueous extraction becomes a more realistic scenario for extraction from dry biomass such as silage, which is available all year round and allows the continuous running of the hypothetical extraction plant.

In principle, the process of aqueous protein extraction requires the following steps: protein is first solubilized by using an alkaline solvent, before being concentrated by either steam injection, ultrafiltration, or acid precipitation.\textsuperscript{145} Dale et al. provide a model protein-extraction process designed for biorefinery integration, which can also be utilized in combination with the biogas plant.\textsuperscript{146} This model will be further elaborated below. The extraction is carried out in two steps, increasing the final protein recovery by completing most of the extraction in the first step and recovering the remaining protein in the second. These two steps are intermediated by the ammonia fiber explosion (AFEX) treatment, which allows the removal of remaining unextracted protein in the biomass locked in fiber structures.\textsuperscript{148} The extractions require liquid anhydrous ammonia treatment of the solids at high pressure, combining physical and chemical effects that result in the solubilization of lignin, hemicellulose hydrolysis, and decrystallization of cellulose.\textsuperscript{149} Figure 5 provides an overview of the process and its conditions.

The entire process uses NH\textsubscript{3} as an alkaline solvent to separate the protein from its cellulosic biomass, which is then recycled back into the system at various steps in the extraction process. Figure 6 illustrates the protein-extraction process, showing the main processes and product outputs from each step. The protein yield from the first protein extraction was estimated to be ~60% with a further extraction of ~60% of the remaining protein in the second extraction, adding up to over 80% of the total extracted protein.\textsuperscript{146} This, however, was an optimistic assumption that considered a mature technology with high protein yields. These high yields appear to be attainable, as Chiesa and Gnansounou (2011)\textsuperscript{61} report that lower lignin feedstocks (4%–6%) resulted in larger protein yields (50%–75%) from the cytoplasmic protein fraction after AFEX treatment. Cup plant contains on average 6% lignin in the dry matter, so a valid assumption can be made with the optimistic extraction value.\textsuperscript{97}
Another biological pathway for protein extraction is provided by insects. Insects are a promising protein source for fish and livestock feed. The larvae of the black soldier fly (*Hermetia illucens*) is already used commercially for organic waste and manure treatment to reduce its mass, moisture, content, and odor, while serving as valuable feed ingredient for cattle, pig, poultry, and fish farming. Black soldier fly larvae (BSFL) have a high protein content (37%–63% dry matter base) and up to 49% fat, and also contain several macro- and micronutrients important for animals as well as humans. These characteristics suggest that BSFL might provide a suitable biological method for protein extraction from cup plant prior to feeding it into the biodigester.

This was pre-tested by feeding BSFL with dried cup plant stems and leaves (separated) in a batch test. About 250 BSFL were raised on 100 g of dried leaves and another 250 BSFL on 100 g of dried stems in a two-chamber box (60 L) with moisture control. The dried cup plant leaves were almost...
completely eaten by the BSFL, while the stems remained largely untouched after 14 days.

Consequently, biological protein extraction from cup plant prior to biodigestion is a promising, yet efficient approach to make additional use of the protein, e.g. as feed supplement at EPH or for selling. However, the composition and nutritional value of BSFL depends largely on the composition of the feedstock. Thus, further experiments must be conducted to analyze BSFL composition reared on cup plant.

**Protein extraction residue as biogas feedstock**

In most previous studies, residue from protein extraction such as press cake is often used as a low-quality feed, yet, aside from protein, the other main output of the protein extraction and AFEX treatment is the residual biomass, consisting of hydrolysate. Integration of aqueous protein extraction with EPH’s biogas plant allows the valorization of the cup plant silage for use of biomass as a better quality digester feedstock. This process results in sugars, so this pretreated slurry, obtained at the end of the process, becomes a highly suitable substrate for biogas fermentation. It can be concluded that the hydrolysis carried out through the AFEX pretreatment allows the bypass of the initial hydrolysis step in the initial phases of anaerobic digestion which occurs in the biogas plant digester. Pre-treatment on lignocellulosic biomass designated for biogas production is a widely researched topic, in which the liberation of more readily fermentable sugars provides easier access for microorganisms, allowing anaerobic digestion to proceed faster. Such is the use of aqueous ammonia soaking (AAS) as a pretreatment. This method has been proven to be suitable for anaerobic digestion by increasing the methane yield given that microbial activity is not limiting. Using the same reaction reagents, Zheng et al. (2014) review AFEX as an independent step in biomass pre-treatment, and find it to be a highly effective method for digestibility and degradability improvement. Nonetheless, the review mentions the need for more research on the method, particularly concerning the suitability of the process and the treated biomass for use as feedstock for biogas production. More research is required in the field to ensure that biogas yields are not affected by the pretreatment of cup plant silage.

**Scenarios in substitution of soy-based protein**

To substitute soy-based protein with cup plant-based protein, we will assess two scenarios in the context of EPH. The first involves substitution of feed for the current pig farming, and the second presents the future scenario in which livestock farming is completely shifted to dairy cattle. The nutritional value of proteins can be described by the composition of essential amino acids (AA), shown in bold in Table A3. To determine the suitability of cup plant-based protein as a soybean protein substitute, the AA composition characteristics were analyzed. Table A3 shows that the of essential AA in cup plant out of the total AA, is 42% and 47% respectively, in comparison to soybean, 45%. Taking these numbers into account, it can be assumed that the quality across the two protein sources is equal. The values for the two datasets for cup plant vary much more than between the two soy datasets. There is no standardized information on the AA composition of cup plant since there is limited amount of research available on cup plant. This is partly due to different cup plant varieties grown in different geographical conditions, likely impacting the nutritional content.

In the current scenario, EPH collectively manages 6180 pigs, consisting of 250 sows and 5930 fattening pigs, as well as 110 dairy cows (status: 2016). These assumptions on numbers as reported by EPH will be used for further calculations. Dairy cows have high energy and protein requirements due to the production of milk, with a cow needing up to 4% of its weight in dry matter feed daily. Assumptions and calculated values for protein requirement are shown in Table A4. These assumption disregards the different protein requirements needed for different sizes, breeds, stages of pregnancy, or milk production of the livestock and therefore the median data values are used.

In examination of the calculated protein requirements for the two scenarios of livestock farming, namely 2779 Mg and 2800 Mg for the current pig and future dairy cow scenarios respectively, the difference of 0.75% in protein requirements is deemed negligible. From here on, the two scenarios will be disregarded and will be considered to have the same protein requirements of 2.8 Mg of protein daily.

Next the potential input and possible output of protein extraction was quantified based on two scenarios of percentage of cup-plant cultivation, namely 44% (current) and 70% (future) of the total farmlands of area 763 ha. The DMY of cup plant is taken as 15 Mg ha⁻¹ with a crude protein (CP) content of 9.8% DM – according to analyses on whole cup plant carried out at EPH. A calculation of the hypothesical cup plant silage input and extracted protein output is shown in Table 1. For the sake of simplicity, the output of the protein extraction system is assumed to be of 100% purity. The calculations in Table 1 show the potential of soybean protein substitution with cup plant protein in the different scenarios consisting of 44% and 70% of cup plant cultivation.
in existing farmlands and the low and high possibilities of extraction efficiency, 40% and 80% respectively. The results show that in the current case with low extraction efficiency, a pessimistic scenario, there is a theoretically achievable substitution of 19%. However, in an optimum scenario with high cultivation and high extraction efficiency there is a possible substitution rate of 61% of soy-based feed with cup plant-based protein.

The simplified assumptions in the scenarios mentioned above must be taken into consideration. They assume that the purity of the produced protein is near to or equivalent to 100%. Furthermore, there have not been studies explicitly comparing the nutritional quality of the protein in cup plant and soybean nor its bioavailability; therefore the assumed substitution of 1:1 may not hold true. Losses within the protein extraction system are not considered. The protein extraction efficiency is therefore assumed to be 100%.

### Nutrient recovery from digestate

Over the past 200 years, agricultural intensification has not only significantly increased crop production and ensured global food security; it has also created a dependency on fertilizers and contributed to environmental pollution, mainly due to manure and mineral fertilizers containing nitrogen (N) and phosphorus (P). Mineral uptake by the crops is not 100% efficient, and fertilizer not taken up by plants often ends up in water bodies and can lead to eutrophication when present in excess amounts. Phosphorus is obtained by mining, which releases radioactive compounds and heavy metals into the environment. The global phosphorus demand is constantly rising, and currently 90% can be attributed to agricultural production, exclusively originating from non-European phosphate rock reserves. In nature, there is no substitute that can replace phosphorus in photosynthesis. The European Commission has therefore listed phosphate rock as a critical raw material, indicating its high economic value and endangered supply. Besides ecological impacts, political dependencies, and the availability of resources, the production and transport of mineral fertilizers also uses significant amounts of fossil energy.

As part of the German energy transition, the nationwide installation of biogas plants has been extensively supported and encouraged. The secondary product of biogas production is the residual biomass or digestate that has so far mainly been used as organic fertilizer due to its high N and P content. The EPH is no exception as they use a large share of their digestate as organic fertilizer. However, to counteract negative ecological effects arising from the overuse of N and P contained in the digestate, stricter fertilizer regulations have been implemented by the German federal government.

The overproduction of digestate has therefore created new challenges for waste disposal. This can also be observed at the EPH, where the construction of a third storage tank with a volume of 6600 m³ for access digestate has recently been completed.

Altogether, these arguments provide reasons to find ways to recover phosphorus from digestate and to derive products that can be reintegrated into agricultural business cycles. Extracting phosphorus from digestate could, in theory, result in a solid, P-rich component that can be used for fertilization, and in a less nutrient-rich residual liquid that could be more widely applied on the fields than digestate. The use of hydrothermal carbonization on anaerobic digestate has the potential to mitigate several problems related to the use of digestate at once. In combination with acid leaching and struvite (magnesium ammonium phosphate = MAP) precipitation a high phosphate recovery rate can be achieved and therefore a step can be taken towards a more sustainable resource utilization in agricultural production. Based on the comparison of Tambone and Adani (2017) the properties of digestate are assumed to be comparable to those of sewage sludge.

### Process description of hydrothermal carbonization (first step)

Hydrothermal carbonization (HTC) is a thermochemical process converting biomass into lignite-like products (hydrochar), which takes place in water under subcritical
conditions.\textsuperscript{75,167–170} The combination of temperatures between 180 °C and 250 °C\textsuperscript{171} and pressures between 20–80 bars\textsuperscript{161} forms a process that replicates the natural process of coal generation. During the process, both biomass and water are heated in a pressurized reactor for several hours, which reduces the hydrogen and oxygen contents of the feed and increases its carbon content and energy density.\textsuperscript{172} Besides hydrochar, water-soluble compounds and a negligible amount of CO$_2$ are produced.\textsuperscript{161} The pressurized water is present in subcritical conditions, referring to a temperature range between its boiling point at 100 °C and its critical point at 374°C. Under these conditions, water acts as a catalyst.\textsuperscript{173,174}

Hydrothermal carbonization takes place at elevated temperatures, so that cellulose chains are hydrolyzed to different glucose oligomers.\textsuperscript{161} These sugars are degraded into acids and acetaldehydes \textsuperscript{175} which are converted into furfurals.\textsuperscript{176} The furfural undergoes polycondensation, the products of which form the more stable aromatic ring compounds (hydrochar).\textsuperscript{177} As water is used as a reaction medium, the conversion process creates a wet biomass similar to digestate.\textsuperscript{75} The main parameters influencing HTC are temperature, pH, and carbonization time. The modification of these process parameters and their effects on the rate of phosphorus recovery as well as the hydrochar formation are described in detail in Stutzenstein \textit{et al.} (2018).\textsuperscript{75} It is stated that temperature and pH have a strong influence on the nutrient recovery whereas time has only a minor effect. The special properties of supercritical water favor the degradation of biomass at high temperatures\textsuperscript{171} and low pH values.\textsuperscript{75} An optimized temperature for nutrient recovery was found to be around 165 °C, a temperature where carbonization does not occur to a high degree. The recovery of phosphorus in hydrochar is maximized at a very alkaline pH, around 8.

**Benefits of hydrothermal carbonization of digestate**

Hydrothermal carbonization using digestate may help solve several challenges associated with intensive agricultural production. Bacterial pathogens that were formally present in the digestate are killed, unpleasant odors are neutralized, and organic compounds that were not degraded in anaerobic digestion can be further utilized.\textsuperscript{162} Anaerobic digestion can therefore be regarded as a pre-treatment, resulting in a biomass input for HTC whose cell structure has already partially been degraded.\textsuperscript{161} The hydrochar that is obtained by thermally decomposing the organic compounds has a higher C content compared with the digestate. This corresponds to a higher heating value. Compared to the digestate, the hydrochar is also more hydrophobic. This facilitates the separation of digestate into solid and liquid compounds,\textsuperscript{172,178} a process that happens after the reactor has been cooled down to stop the carbonization.\textsuperscript{75} Many different filtration processes can be used to optimize the separation.\textsuperscript{140} Besides being used within the phosphate extraction process, the hydrochar can be used in gasification,\textsuperscript{179} combustion\textsuperscript{180,181} and as a growth medium in horticulture.\textsuperscript{182} As the hydrochars have a high ash content, they are also used as a feedstock for high value activated carbon for wastewater treatment.

The use of HTC as a first step in the P extraction process is beneficial because it creates a completely sanitized product with a high heating value, the hydrochar. It also immobilizes the heavy metals contained in the digestate into the solid phase (hydrochar).\textsuperscript{183,184}

**Leaching and struvite precipitation (second and third steps)**

Another product of HTC is the process liquid, which contains large amounts of organic acids and ammonium, and depending on the digestate composition it may also be rich in phosphorus.\textsuperscript{185,186} The suitability of P extraction exclusively from the liquid phase requires further research. But as many sludges also contain metal salts, phosphorus is predominantly bound in the hydrochar and cannot be recovered by HTC alone. In further steps, P can thus be separated from the solid phase by acidic leaching and recovered as struvite by precipitation.\textsuperscript{185}

In the beginning, citric acid is added to the hydrochar to initiate phosphorus leaching at a pH of 2–5.\textsuperscript{185,187} The acidic sludge is filtered and the permeate is precipitated in a further reactor where the struvite precipitation takes place. The retained material, which still contains considerable amounts of P, is used again in the process of acid leaching.\textsuperscript{187} NaOH is added to the permeate substance in the third reactor to increase the pH to 8–9 and mixed with the ammonium-rich process liquid originating from the HTC treatment. MgCl$_2$ is added as a magnesium source, leading to Eqn (1) for struvite precipitation:

\[
\text{Mg}_2^+ + 2\text{NH}_4^+ + 3\text{H}_2\text{PO}_4^- \rightarrow \text{Mg}\text{NH}_4\text{PO}_4 \cdot 6\text{H}_2\text{O} + n\text{H}^+ \tag{1}
\]

with n = 0; 1; 2.

Struvite (MAP) is formed when magnesium, ammonia, and phosphate are present in water at a 1:1:1 mole to mole ratio and obtained by an additional filtration step. The filtrate liquid is applied on the fields as organic fertilizer. The whole process is schematically described for the case of the EPH in Fig. 7. The choice and concentration of acid, base, and magnesium source in the two process steps as well as the influence of the pH are topics of current research.\textsuperscript{76,185,187} They influence the recovery time and the rate of recovered struvite, and are very relevant cost factors.\textsuperscript{187} The related
The literature would have to be reviewed and the process parameters adapted for the case of EPH.

**Application of struvite extraction at the EPH**

A sample of digestate that was taken at the EPH on January 21, 2019, contained 24.4 g P (as P$_2$O$_5$) kg$^{-1}$ DM digestate (or 1.3 g P kg$^{-1}$ wet mass) with a dry matter content of 5.2%. This is equivalent to a total P concentration of 2.4% in the digestate. The pH was measured as 7.8. During HTC treatment the P contained in the digestate can be bound in the sanitized hydrochar and leached into the process water once its pH is reduced. By struvite precipitation and an additional filtration step, 60%–90% of the phosphate (as P$_2$O$_5$) can be removed as a solid while the P content in the remaining liquid is reduced.

The installed biogas plant at the EPH produces 100 m$^3$ of digestate per day. Considering its high water content, it is assumed to have a density similar to water (1 m$^3$ = 1 Mg). Based on the daily operation of the plant, this amounts to 36 500 Mg of digestate produced per year. Taking the digestate sample of January 21, 2019 as a reference, the potentially yearly recovered phosphate (as P$_2$O$_5$) thus ranges from 28 470 kg (60%) to 42 705 kg (90%) (Table A5). In a case where 100% of the necessary P for the cultivation of cup plant would need to be provided by mineral fertilization, this would require 30 kg ha$^{-1}$ phosphate. The presented scenarios of 60%–90% phosphate extraction would thus allow a P provision for an area of 949–1423 ha respectively (Table A5). If the total farmland of EPH (763 ha) were to be used for the cultivation of cup plant, the extracted P would be sufficient to meet the demand in P.

According to the approach by Meyer et al., the P$_2$O$_5$ content in the permeate (struvite) is approximately 25%–28%, which is close to the composition of pure struvite. For the calculation of struvite extraction potentials at the EPH, phosphate content of 25% in the solid recyclate is assumed accordingly. By applying the three process steps, HTC, acid leaching, and struvite precipitation, for the case of the EPH, a possible struvite yield of 113 880 kg to 170 820 kg depending on the P recovery rate may be achieved.

It must be considered that the phosphate concentration in the digestate depends on the biogas feedstock. As the silage composition at the EPH varies constantly, the expected recovery of struvite will vary in a similar manner. Struvite is highly suited for use as a fertilizer and can be used at the EPH directly to substitute a proportion of the applied mineral fertilizer. The remaining process liquid (filtrate liquid) could be applied on the field and substitute digestate as organic fertilizer as it still contains many nutrients that are beneficial for the soil. This way, the process described would contribute to a valorization of anaerobic digestate, a reduction of the waste disposal problem, and a step towards the reduction of mineral fertilizers.

**Discussion**

Overall, the expansion of cup plant cultivation area from the current 44% to a future 70% of total farmland results in a decreased methane production, producing 742 095 m$^3$ less methane in comparison. This is due to maize having a higher DMY than cup plant and a higher methane yield per hectare. It should be noted that the current DMY and methane yields of the cup plant could potentially be increased in the

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*Figure 7. Schematic description of phosphate extraction process, adapted from references 185,187.*
future. Due to its fairly recent use as a biogas substrate, a lot of research, e.g. on the management of both fertilization and harvest, is still missing for cup plant. Consequently, there may be a great potential for improvement of cup plant methane yields. In this case, EPH has a special competitive advantage with their extensive work in cup plant breeding, which has resulted in improved seed quality. As high-quality seeds are not available, in general seedlings are used for cup-plant cultivation. The patented seed-based establishment procedure from EPH, however, is already at a high technology readiness level.\textsuperscript{131} The specialization of EPH’s business operations on cup plant is therefore rather unique. If research in this field is intensified by EPH, it might allow for an increase in both methane yields and the generation of additional income through seed-based cup-plant establishment.\textsuperscript{131} But the central argument for the choice of cup plant is its numerous ecological advantages compared with maize and similar annual energy crops.\textsuperscript{71} Moreover, it can be well adapted to European sites and has low cultivation requirements.\textsuperscript{86}

A lot of information is still missing regarding the quantity of soy imported at EPH and the current animal feed composition. As soy is associated with land grabbing, soil erosion, and deforestation of rainforests, the substitution of soy by an alternative protein source, ideally from EPH’s own production, should be considered. Alternative protein will need to have all the appropriate AAs supplemented by soy. Soy is cheap compared to other protein feed and is available year round, hence an alternative feed replacing it should be economically viable and similarly readily available. Review analysis has shown global negative environmental and socio-economic impacts caused by soy due to the dependency on supplier countries. It is therefore important to focus on securing sustainable protein production for animal feed.

Protein extraction from cup-plant silage is a good prospect for the substitution of soy protein. The soybean yield for cultivation in Brazil is at an average of 3.34 Mg ha\textsuperscript{−1}.\textsuperscript{155} Taking the protein content to be 44.3\%\textsuperscript{180} this is equivalent to 1479 kg protein ha\textsuperscript{−1}.\textsuperscript{1} Following through from the optimistic scenario in our calculations with 628.1 Mg extracted CP (61\% substitution) (Table 1), there is an annual saving of approximately 424.7 ha worth of soybean cultivation in Brazil. The implications of this are a reduced ecological footprint as well as negative social impacts related to the feed production. The integration of feed protein production from already existing agricultural systems translates into savings in material, energy, and financial capital, thus increasing the overall sustainability of the system.

In a realistic scenario, the purification of the protein extract to a high level of purity may require further concentration steps than those mentioned, requiring more energy and material input. The intrinsic nutritional quality of leaf proteins is quite high and it is thus considered worthy of further investigation.

There is concern about the overall effect of protein extraction on the resulting digestate. Maize and cup-plant cultivation require different levels of NPK fertilizer\textsuperscript{190} and as the concentration of N in the digestate is reduced, the levels of P and K in the digestate must be taken into account. Consequently, following phosphorus extraction, the digestates’ nutritional content must be evaluated to ensure that all fertilizer demands of the crop are met and that all nutrients are bioavailable.

Several aspects of the technical and financial feasibility of such a phosphorus recovery integration at the EPH require further investigation. These include: (i) the extent to which the process liquid is directly applicable on the field, and (ii) the necessity of additional steps to improve its characteristics as organic fertilizer (i.e. for lowering its pH after the struvite precipitation).

It should be kept in mind that the P demands of the soil for the cultivation of cup plant and maize are comparatively low. Hence, the avoidance of P toxic overuse on the soil can be an incentive for the P content reduction in the digestate. However, the presented high phosphate extraction rates are only obtained by optimized inputs linked to high process costs, especially in the case of acid and base additions. It needs to be questioned how high the extraction rates really need to be to meet legislative requirements for the use of the process liquid as organic fertilizer, on one hand,\textsuperscript{185} and maintaining overall profitability on the other. Moreover, little information is found in literature regarding the quality, value, and demand for recycled nutrients in general.\textsuperscript{76} In respect to the quality, it is likely that these products will still be classified as waste products from a legislative perspective. The demand for recycled struvite is currently assumed to be quite low because of the constant decline of ‘fresh’ phosphate rock prices in the past ten years.\textsuperscript{193} Since the use of recycled phosphate as fertilizer entails the potential of returning a P source to the soil that is free of heavy metals, recyclates such as struvite may become more interesting for the agricultural sector in the future. In the practical implementation of the process at the EPH and the use of both the struvite and the process water, it would need to be ensured that heavy metals do not find their way back into the field. Further, this paper assumes similar properties of digestate to sewage sludge. A sound comparison of the two sludges would be advisable to verify the interacting influences of the process parameters.
Conclusions

In this study, the potential for optimization of the current material cycles was explored in the context of the planned changes at EPH in the near future: the switch from pig to dairy cow farming and the upscaling of cup plant as a substitute for maize. Attempts have been made to give a holistic picture of the current system operations and to show the effects of the changes that are already planned by the farmers, shown by the change in the material flow (Fig. 3).

Correct feed substitution is important not only for animal health and performance but to minimize ongoing negative environmental impacts. As a biogas substrate, cup plant should be chosen over maize. Despite a lower methane yield it has several ecological advantages. The large lacuna in cup plant research could yield substantial improvements, closing the yield gap between cup plant and maize, and EPH’s specialization in cup plant gives it a competitive advantage to increase (financial) returns. We highlighted the potential of existing technological approaches in cup plant protein extraction and phosphate extraction from digestate. Relevant process parameters for the latter such as pH, temperature, and carbonization time, and its influences are presented and the exemplary phosphate extraction potential (as P₂O₅ in struvite) was modeled. Based on a sample of EPH’s digestate, the possible extracted phosphate yield was calculated.

Equally promising is the protein extraction from cup plant silage. The potential for protein recovery is high considering the technology in leaf protein extraction that is applicable in EPH’s situation. As a modest assumption, 19% protein substitution is a good starting point to start small-scale extraction plants while more optimistic scenarios have the prospect of even higher yields. It can be concluded that nutrient extraction from both the input and output side of the biogas production can be highly beneficial in improving nutrient recovery and closing material cycles, utilizing materials that would otherwise be stored. In view of the changing landscape in biogas legislation it is recommended that the function of EPH’s biogas plant as a predominant provider of renewable energy is reconsidered. Instead, its role could be broadened to that of a holistic biorefinery.

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## Appendix

### Table A1. Calculations for scenario 1: Comparison of current methane production with methane production from 100% cup plant substrate.

| ScENARIO/ASSUMPTION | CALCULATION |
|----------------------|-------------|
| CURRENT BIOGAS PRODUCTION | 1000 m³ biogas h⁻¹ 1000 m³ biogas h⁻¹ x 24 h = 24 000 m³ biogas d⁻¹ |
| 75% USED FOR METHANE PRODUCTION | 24 000 m³ biogas d⁻¹ x 75.0% = 18 000 m³ biogas d⁻¹ |
| METHANE PRODUCTION (ASSUMING 56.5% METHANE CONTENT OF BIOMASS) | 18 000 m³ biogas d⁻¹ x 56.5% = 10 170 m³ biogas d⁻¹ |
| 100% CUP PLANT SUBSTRATE | 200 Mg VS d⁻¹ |
| SUBSTRATE-SPECIFIC METHANE YIELD OF CUP PLANT | 0.232-0.275 m³N kg⁻¹ VS⁻¹, average: 0.2535 m³N kg⁻¹ VS⁻¹ |
| 75% USED FOR METHANE PRODUCTION | 200 Mg VS d⁻¹ x 75% = 150 Mg VS d⁻¹ |
| METHANE PRODUCED | 150 Mg VS d⁻¹ x 0.2535 m³N kg⁻¹ VS⁻¹ = 38 025 m³N d⁻¹ |

VS = volatile solids.

### Table A2. Calculations for scenario 2: Up-scaling of cup plant cultivation area from 44% to 70% of total farmland (a reduction of maize cultivation area by 26%).

| SCENARIO/PARAMETER | VALUE/CALCULATION |
|--------------------|--------------------|
| CURRENT FARMLAND OF EPH | 763 ha |
| 26% LESS LAND FOR MAIZE CULTIVATION | 763 ha x 26% = 198.38 ha |
| AVERAGE ANNUAL YIELD OF MAIZE | 17.5 Mg VS ha⁻¹ |
| LOST MAIZE VS | 17.5 Mg VS ha⁻¹ x 198.38 ha = 3471.65 Mg VS |
| 75% USED FOR METHANE PRODUCTION | 3471.65 Mg VS x 75% = 2603.74 Mg VS |
| SUBSTRATE-SPECIFIC METHANE YIELD OF MAIZE | 21% higher than methane yield of cup plant 0.2535 m³N kg⁻¹ VS⁻¹ x 121% = 0.306735 m³N kg⁻¹ VS⁻¹ |
| LOST METHANE YIELD FROM MAIZE | 2603.74 Mg VS⁻¹ x 0.306735 m³N kg⁻¹ VS⁻¹ = 798 657.42 m³N kg⁻¹ |

VS = volatile solids.

### Table A3. Comparison of the amino acid profile in cup plant and soybean as a percentage of total protein.

| AMINO ACID | CUP PLANT | SOYBEAN |
|------------|-----------|---------|
| Asp        | 8.5       | 9.4     |
| Thr        | 3.3       | 4.5     |
| Ser        | 3.3       | 5.0     |
| Glu        | 21.5      | 9.3     |
| Pro        | 2.5       | 6.6     |
| Gly        | 3.6       | 4.8     |
| Ala        | 3.1       | 4.3     |
| Val        | 4.4       | 4.4     |
| Ile        | 3.4       | 4.1     |
| Leu        | 7.4       | 9.7     |
| Tyr        | 2.9       | 6.8     |
| Phe        | 3.8       | 4.1     |
| Lys        | 2.4       | 4.5     |
| His        | 1.7       | 1.4     |
| Arg        | 6.2       | 4.5     |
| Cys        | 2.2       | –       |
| Met        | 2.5       | 3.5     |

**Total essential AA**

| Reference | 192 | 144 | 193 | 194 |
Table A4. Overview of numbers used in the assumption of protein substitution (data adapted from\textsuperscript{146,156,195}). (A) Shows the basic assumptions for the calculation of CP requirement per day. (B) and (C) show the calculations using values derived in (a) for the current and future scenarios of animal cultivation respectively.

(A)

| Parameter                  | Unit   | Cows | Sows | Fattening pigs |
|----------------------------|--------|------|------|----------------|
| Weight                     | kg     | 500  | 30–60| –              |
| Dry matter feed            | % wt.  | 4    | –    | –              |
|                            | kg d\(^{-1}\) | 20   | 2.5  | 0.401          |
| CP requirement             | % DM feed | 14   | 15   | –              |
|                            | kg d\(^{-1}\) | 2.8  | 0.375| 0.401          |

(B)

| Parameter                  | Unit   | Cows | Sows | Fattening pigs |
|----------------------------|--------|------|------|----------------|
| Number of animals          | –      | 110  | 250  | 5930           |
| CP requirements            | kg d\(^{-1}\) | 308  | 93.75| 2377.93        |
| Total CP requirements      | kg yr\(^{-1}\) | 112420| 34218.75| 867944.45     |
| Total livestock requirement| kg yr\(^{-1}\) | 1014583.2| –     | –              |

(C)

| Parameter                  | Unit   | Cows |
|----------------------------|--------|------|
| Number of animals          | –      | 1000 |
| CP requirement             | kg d\(^{-1}\) | 2800 |
| Total livestock requirement| kg yr\(^{-1}\) | 1022000|

Table A5. Potential phosphate extraction and substitution quantities at the EPH.

| Parameter                                        | Value       | Calculations                                      |
|--------------------------------------------------|-------------|---------------------------------------------------|
| Digestate produced/day                           | 100 m\(^3\) d\(^{-1}\) |                                                    |
| Digestate produced/year                          | 36500 Mg    |                                                    |
| Phosphate recovered (0.6% d\(^{-1}\))            | 78 kg       | 0.6 × 1.3 g kg\(^{-1}\) × 100 Mg                  |
| Phosphate recovered (0.6% yr\(^{-1}\))           | 28470 kg    | 78 kg × 365                                       |
| Phosphate recovered (0.9% d\(^{-1}\))            | 117 kg      | 0.9 × 1.3 g kg\(^{-1}\) × 100 Mg                  |
| Phosphate recovered (0.6% yr\(^{-1}\))           | 42705 kg    | 117 kg × 365                                      |
| Recycled struvite obtained (at 0.6% phosphate yr\(^{-1}\) and with 25% struvite recycling efficiency) | 113880 kg | 28470 kg × 1/0.25                               |
| Recycled struvite obtained (at 0.9% phosphate yr\(^{-1}\) and with 25% struvite recycling efficiency) | 170820 kg | 42705 kg × 1/0.25                               |
| Possible area output due phosphate fertilizer from extracted P\(_2\)O\(_5\), (0.9%-scenario) | 949 ha | 28470 kg (30 kg ha\(^{-1}\))\(^{-1}\)               |
| Provision of P from extracted P\(_2\)O\(_5\), (0.9%-scenario) | 1423.50 ha | 42705 kg (30 kg ha\(^{-1}\))\(^{-1}\)               |