Small-scale biochar production on Swedish farms: A model for estimating potential, variability, and environmental performance

Elias S. Azzi [a, *], Erik Karltun [b], Cecilia Sundberg [a, c]

[a] Department of Sustainable Development, Environmental Engineering and Sciences (SEED), KTH Royal Institute of Technology, Sweden
[b] Department of Soil and Environment, Swedish University of Agricultural Sciences (SLU), Uppsala, Sweden
[c] Department of Energy and Technology, Swedish University of Agricultural Sciences (SLU), Uppsala, Sweden

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ABSTRACT

Several small-scale pyrolysis plants have been installed on Swedish farms and uptake is increasing in the Nordic countries. Pyrolysis plants convert biomass to biochar for agricultural applications and syngas for heating applications. These projects are driven by ambitions of achieving carbon dioxide removal, reducing environmental impacts, and improving farm finances and resilience. Before policy support for on-farm pyrolysis projects is implemented, a comprehensive environmental evaluation of these systems is needed. Here, a model was developed to jointly: (i) simulate operation of on-farm energy systems equipped with pyrolysis units; (ii) estimate biochar production potential and its variability under different energy demand situations and designs; and (iii) calculate life cycle environmental impacts. The model was applied to a case study farm in Sweden. The farm's heating system achieved net carbon dioxide removal through biochar carbon sequestration, but increased its impact in several other environmental categories, mainly due to increased biomass throughput. Proper dimensioning of heat-constrained systems is key to ensure optimal biochar production, as biochar production potential of the case farm was reduced under expected climate change in Sweden. To improve the environmental footprint of future biochar systems, it is crucial that expected co-benefits from biochar use in agriculture are realised. The model developed here is available for application to other cases.

1. Introduction

By managing land, humans produce biomass resources that provide food, materials, and energy services. Since the industrial revolution, land use changes have emitted around one-third of cumulative anthropogenic carbon emissions, while fossil fuel combustion has emitted the remaining two-thirds (Berndes et al., 2012). Agricultural practices have also been significant drivers of biodiversity loss and environmental degradation. Enabling farmers worldwide to reduce the environmental footprint of land use, while maintaining and increasing biomass production, is a long recognised challenge (Vásquez et al., 2018). If humanity fails to cut its greenhouse gas emissions sufficiently fast, the internationally agreed climate goals will also require deployment of carbon dioxide removal (CDR) technologies (IPCC, 2018). Farmers can potentially contribute to CDR through their farming practices and energy systems.

Among the practices investigated to reduce the environmental impacts of farming activities and achieve CDR, biomass pyrolysis with biochar production is an option often deemed cost-effective compared with other CDR technologies (Smith et al., 2019). Small-scale pyrolysis plants have even begun to be installed on farms in Sweden and the other Nordic countries. Pyrolysis reactors, in combination with existing heat pumps and electrical heaters, provide the heat needed for farm activities, while electricity is mostly taken from the grid. Pyrolysis reactors are currently used for heating residential buildings and animal barns during the cold winter months, but other uses such as greenhouse heating, post-harvest drying of grain and fuel production are envisioned. The pyrolysis plants are fed with different types of biomass, e.g. commercial wood pellets, self-harvested woodchips, or agricultural residues and wastes.

Biochar, the co-product of these pyrolysis energy systems, is a solid carbon residue similar to charcoal. When spread on agricultural land, biochar decomposes slowly enough to act as a carbon sink, effectively removing carbon dioxide from the atmosphere for centennial time scales (Leng et al., 2019). Its use in agriculture is

also expected to provide other environmental and economic benefits (Nair et al., 2017). While biochar production has started in Sweden, biochar use on farms is still at an early stage. Financial compensation in the form of carbon credits is part of the farmer's expectations, and voluntary carbon markets are already experimenting with pricing of biochar carbon credits (e.g. puro.earth & ecoera.se). Additional national support policy is expected as part of Sweden's net-zero climate targets. Therefore, comprehensive environmental evaluation and recommendations on the design of on-farm pyrolysis systems are needed for sound policy development.

Life cycle assessment (LCA) is a widely recognised method for assessing the potential environmental impacts of systems, and has been applied to various pyrolysis systems (Tisserant and Cherubini, 2019). However, LCA studies on pyrolysis generally focus on climate change as a single impact category. In addition, operational constraints, start-up and shut-down of plants are under-represented in LCA studies of new technologies such as pyrolysis. These effects are of particular importance for small-scale systems, which are usually less well optimised. Moreover, on Swedish farms biochar production is currently coupled to heat demand, which is limited, weather-dependent, and increasingly affected by climate change. Therefore, biochar production, which is expected to contribute to climate change mitigation, will potentially be hindered by climate change in the Nordic region, a fast-warming part of the world. Such feedback loops and long-term effects are not commonly included in LCA, but are important for biochar producers and for the design of well-functioning pyrolysis systems.

To bridge the current knowledge gaps on pyrolysis operation and the limitations of static LCA models, this study examined inclusion of energy system models in LCA. In particular, unit commitment models (Saravanan et al., 2013) are commonly used to simulate the operation of complex energy systems and optimise the design of e.g. national electricity grids (Koltsaklis and Dagoumas, 2018) or large district heating networks (Lundström and Wallin, 2016). Recently, pyrolysis technologies for large-scale electricity production have been included in such energy system models (Li et al., 2019). Moreover, unit commitment models now include some environmental aspects in their multi-objective optimisation. For instance, greenhouse gas emissions were included by Li et al. (2019), and taxes on pollutant emissions were included by Atabay (2017). However, these improvements are not complete LCA.

The main aim of this study was to analyse farm-scale biochar production integrated to local heat energy systems, and its life cycle environmental impacts. For this purpose, a unit commitment model (Atabay, 2017) was coupled with the LCA software *brightway2* (Mutel, 2017) in order to: (i) simulate operation of on-farm energy systems equipped with pyrolysis units; (ii) estimate biochar production potential and its variability under different energy demand situations, including future climate; and (iii) generate detailed life cycle inventories (i.e. high time resolution, including capital and variable use phase emissions) of farm energy systems, to evaluate their environmental performance. The model was applied to an idealised case study inspired by Lindeborg Farm, a Swedish farm that has been heating its residential buildings through pyrolysis of wood pellets since 2017.

This article is structured as follows. Section 2 describes the model developed. Section 3 provides details of the case study and the various simulations made. Section 4 presents the results of the case study. These are discussed in Section 5, which also includes generalisations and future model development. Section 6 summarises key conclusions regarding on-farm pyrolysis systems.

2. Methods

Two characteristics of small-scale on-farm pyrolysis heating systems are that (i) the heat effectively supplied by the pyrolysis plant is lower than the farm's total heating demand ($H_{pyr} < H_d$), and (ii) the plant is not used at its maximal potential ($H_d < H_{pyr,max}$). This is due to large seasonal variations in heat demand and dimensioning of the plant. The margin for the optimisation of a farmer's energy system thus lies within the interval $H_{pyr} < H_d < H_{pyr,max}$. The model developed in this paper is applied to such cases. The modelling is made in Python, and relies on several open-source libraries, mainly *ficus* − a unit commitment solver for industrial energy systems (Atabay, 2017), and *brightway2* − an open-source framework for advanced life cycle assessment (Mutel, 2017). The new library is available online.[1]

2.1. Modelling workflow

To analyse a farm's biochar-energy system, a five-step workflow was conceived including a) description of the case, b) modelling of energy demand, c) definition of the supply technologies, d) solving of the unit commitment problem, and e) calculation of indicators (Fig. 1).

2.1.1. Case description

In this step, the modeller defines the set of commodities ($c \in \mathscr{C}$), the set of biosphere emissions ($b \in \mathscr{B}$), the set of processes ($p \in \mathscr{P}$), the time frame and the time step of the study ($t \in \mathscr{T}$) that are needed to describe the case (Table 1). Information is collected through interaction with stakeholders and during field visits.

2.1.2. Energy demand

The farm's activities generate demand for several commodities or services, of which space heating and electricity are the most common ones. In this step, demands $d_{c,t}$ for each commodity c at each time step t are compiled from available data (e.g. metering data, bills) or modelled using intermediary data (e.g. local weather data, indoor target temperature, energy declaration to housing agency). The various demands $d_{c,t}$ are then inputs to the unit commitment step.

2.1.3. Energy supply

Farmers have access to different technologies to produce heat such as electrical heaters, heat pumps, biomass combustion, and biomass pyrolysis. In this step, the technologies available on the farm are selected. These technologies or processes are represented by a series of parameters (Table 1), which describe dimensioning and operating conditions of the processes, and flows of commodities and emissions at both full-load and part-load. A list of modelled processes and their parameters is compiled in SI. It can be expanded for modelling future systems e.g. small-scale combined heat-power-biochar pyrolysis or pyrolysis with oil condensation for use as tractor fuel.

2.1.4. Unit commitment

Supplying the farm's demand with the available technologies, while minimising an objective function, is a unit commitment problem. This step uses an open-source implementation of mixed-integer linear programming (MILP) problems initially developed for cost-optimisation of industrial heat and power consumption (Atabay, 2017) and relies on the IBM CPLEX algorithm to solve the

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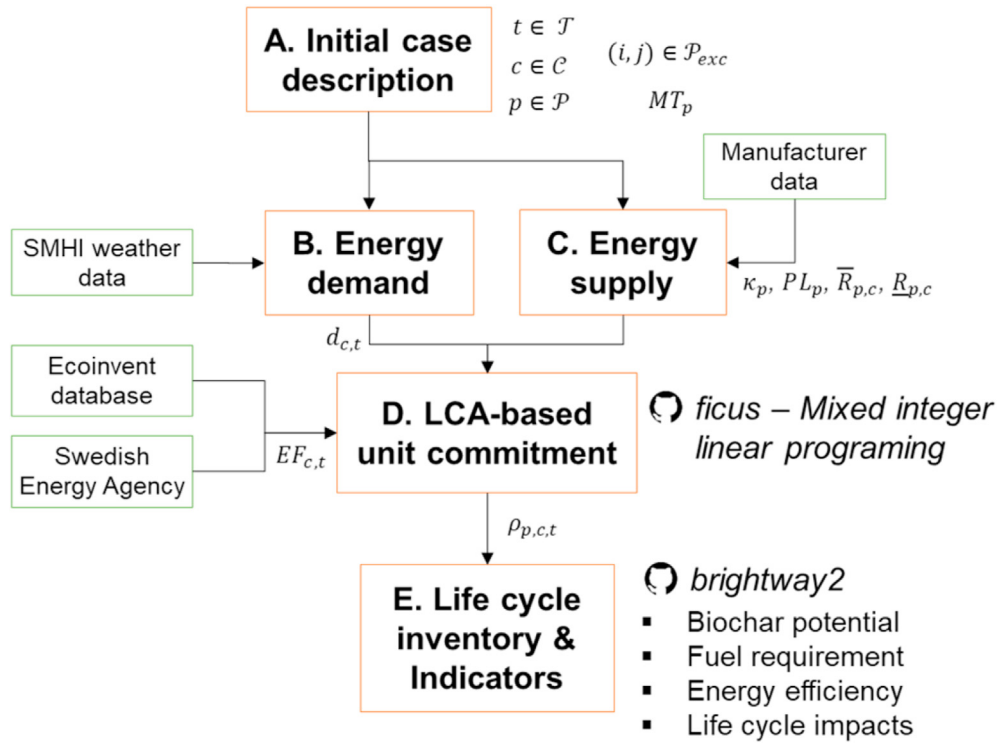[1] https://github.com/ntropy-esa/P2_farm_biochar.

Fig. 1. Workflow for analysis of farm energy systems, combining data collection and modelling steps. See Table 1 for description of notations.

Table 1
Notations for describing the farm-case.

Notation	Description
Indices and sets	
$t \in \mathcal{T}$	Time steps
$c \in \mathcal{C}$	Commodities (e.g. heat, electricity, biochar, pellets)
$b \in \mathcal{B}$	Biosphere emissions recorded (e.g. carbon monoxide, particulates)
$p \in \mathcal{P}$	Processes (e.g. pyrolysis, grid, heat pump; including imports and exports)
$(i,j) \in \mathcal{P}_{exc}$	Pair of processes that cannot be operated simultaneously, subset of $\mathcal{P}^2$
Parameters	
$EF_{c,t}$	Emission factor for commodity c at time t, in $gCO_2eq\ /kWh$
κ_p	Maximum capacity of process p, in kW of reference flow (e.g. 60 kW heat)
PL_p	Part-load capacity of process p, as fraction of maximum capacity κ_p
MT_p	Minimum continuous operation time of process p, in number of time steps
$d_{c,t}$	Demand of commodity c, from process p, at time t, in kW
$\overline{R}_{p,c}$	At full load, ratio between flow of commodity c and reference flow (e.g. 30 kW of pellets for 60 kW heat gives a ratio of 0.5 with heat as reference flow)
$\underline{R}_{p,c}$	At part load, ratio between flow of commodity c and reference flow. These ratios are used to model part load efficiencies.
$\overline{R}_{p,b}$	At full load, ratio between flow of emission b and reference flow (e.g. emissions of nitrogen oxides at a ratio of 7.8 10^{-4} kg h^{-1} kW^{-1})
$\underline{R}_{p,b}$	At part load, ratio between flow of emission b and reference flow. These ratios are used to model part load emissions.
Decision variables	
$\rho_{p,t}$	Capacity at which the process p is run at time t, in kW of reference flow
$\delta_{p,t}^{run}$	Operation mode of process p at time t, binary variable (ON = 1, OFF = 0).
Main output calculated	
$\rho_{p,c,t}$	Input (<0) or output (>0) of commodity c, from process p, at time t, in kW

problem.[2] We reuse similar notations but provide a simplified description of the model, focusing on the features needed to represent on-farm energy systems.

The unit commitment problem in the case of a farm (without energy storage processes) can be summarised by Eqs. (1)–(6). The

objective is to operate the system so to minimise its climate impact (Eq (1)), while meeting the demand (Eq (2)), and operating each plant within its maximum (Eq (3)) and minimum (Eq (4)) capacities.

In its current form, Eq (1) does not allow for excess production: heat dumping to produce more biochar is thus not possible. However, it can be modelled by adding a waste treatment process without heat recovery associated with a demand of biomass waste

treatment (e.g. farmer willing to destroy rotten silage instead of leaving it to decompose on land).

$$\min \sum_{t \in \mathcal{T}} \sum_{p \in \mathcal{P}} \sum_{c \in \mathcal{C}} \rho_{p,c,t} * EF_{c,t} \tag{1}$$

Subject to the constraints:

$$\forall t \in \mathcal{T}, \ \forall c \in \mathcal{C}, \ \sum_{p \in \mathcal{P}} \rho_{p,c,t} - d_{c,t} = 0 \tag{2}$$

$$\forall t \in \mathcal{T}, \ \forall p \in \mathcal{P}, \ \rho_{p,t} \le \kappa_p \tag{3}$$

$$\forall t \in \mathcal{T}, \ \forall p \in \mathcal{P}, \ \rho_{p,t} - \kappa_p \cdot PL_p \ge -\left(1 - \delta_{p,t}^{run}\right) \cdot \kappa_p \tag{4}$$

$$\forall t \in \mathcal{T}, \ \forall (i,j) \in \mathcal{P}_{exc}, \ \delta_{i,t}^{run} + \delta_{j,t}^{run} \le 1 \tag{5}$$

$$\forall t \in \mathcal{T}, \ \forall p \in \mathcal{P}, \ \sum_{k=t}^{t+MT_p-1} \delta_{p,k}^{run} \ge MT_p \cdot \left(\delta_{p,t}^{run} - \delta_{p,t-1}^{run}\right) \tag{6}$$

Two constraints were added to the original *ficus* library (Atabay, 2017), representing situations that appeared in the case study. Eq. (5) restricts the simultaneous use of given plants. Eq. (6) imposes a minimum operation time to each process.

The decision variables are the operation capacity $\rho_{p,t}$ and the operation mode (on/off) $\delta_{p,t}^{run}$ of each process. The latter is a binary variable that can model shutdown of plants if the demand is lower than the part load capacity.

The main outputs of the unit commitment step are the flows $\rho_{p,c,t}$ of each commodity and for each process and time step. It is calculated by Eq (7), which takes into account part load efficiencies. Details on start-up cost calculations for input commodities can be found in (Atabay, 2017).

$$\forall t \in \mathcal{T}, \ \forall p \in \mathcal{P}, \ \forall c \in \mathcal{C},$$

$$\rho_{p,c,t} = \frac{\overline{R}_{p,c} - \underline{R}_{p,c} \cdot PL_p}{1 - PL_p} \cdot \rho_{p,t} + \left(\overline{R}_{p,c} - \frac{\overline{R}_{p,c} - \underline{R}_{p,c} \cdot PL_p}{1 - PL_p}\right) \cdot \kappa_p \cdot \delta_{p,t}^{run} \tag{7}$$

The *ficus* library was also edited to replace the cost minimisation by a greenhouse gas emission minimisation. Prices of input and output commodities were replaced by climate emission factors $EF_{c,t}$ (gCO$_2$-eq kWh^{-1}), using Global Warming Potentials with a 100-year time horizon (GWP$_{100}$).

2.1.5. Indicators and life cycle inventory

The output of the unit commitment step (i.e. $\rho_{p,c,t}$, $\forall p, c, t \in \mathcal{P}$, $\mathcal{C}, \mathcal{T}$) was further processed to calculate various indicators and generate a detailed life cycle inventory in *brightway2*'s format, the open-source framework for life cycle assessment (LCA) (Mutel, 2017). This inventory can be further analysed with the GUI Activity-Browser (Steubing et al., 2020) or directly in Python.

Indicators: Regarding system operation, the model calculates for each plant its average load, operation time, number of start-ups and shutdown. This steps also calculates the annual biochar production and consumption of other commodities.

Life cycle inventory: In this step, the user defines which background processes are used for different stages of the life cycle, e.g. electricity data, plant manufacturing, and solid fuel inputs. The user also quantifies additional biosphere exchanges occurring during the use phase, start-up, and shutdown of the different processes.

Electricity data. To keep the modelling resolution higher than

annual averages and obtain complete life cycle inventories for electricity consumed on-farm, we combined Swedish electricity production data) with Ecoinvent 3.5 processes (with cut-off allocation). These two data sources use different classifications for electricity production processes. Therefore, a correspondence table was also built, based on reports of the Swedish Energy Agency (see SI). The annual apparent electricity mix consumed by each on-farm process p (e.g. pyrolysis, heat pump) for each electricity source on the grid was calculated. For background processes (e.g. plant manufacturing, or pellet production) electricity data was not manipulated.

Biochar carbon sequestration. The (negative) emission factor for biochar represented the amount of C sequestered in biochar for 100 years, as now considered in the 2019 refinement to the 2006 IPCC guidelines for national greenhouse gas inventories (IPCC, 2019). The methodology is based on the biochar's carbon content F_c (tonne C tonne^{-1} dry biochar) and the fraction of biochar carbon remaining after 100 years F_{perm} (tonne C remaining tonne^{-1} initial biochar C), a function of pyrolysis temperature.

Other static LCI data. Unless specified otherwise, the model uses ecoinvent 3.5 cut-off allocation data for biomass fuels, manufacturing, and other inputs. Any other life cycle data can be used.

3. Case study: Lindeborg gård

The idealised case study presented here is inspired from the Lindeborg farm.[3] Section 3.1 describes how the model was parametrised, while section 3.2 describes different simulations made.

3.1. Parametrising the model

3.1.1. Case description

Lindeborg farm is located 120 km south-west of Stockholm, Sweden. The farm has 12 ha of cultivated land, and has 640 m^2 of built area in three buildings (400, 150, and 90 m^2). The farm has two main activities: (i) organic-certified production of various grains (40 tonnes year^{-1}); (ii) a hotel-conference activity, with 3 rooms, 1 individual house, 1 conference room and associated activities (e.g. yoga, cooking classes). The farm is managed by a household, has about 5 part-time employees, and the manager has other business activities. This context forms part of the socio-economic metabolism (SEM) in which the biochar production takes place (Fig. 2).

In 2016, the farm applied for governmental funding to acquire a biochar-producing heating unit. In winter 2017, the farm received its biomass pyrolysis unit from BioMaCon, with a 50 kW heat capacity. The pyrolysis unit runs on wood pellets, a homogeneous feedstock, to ensure safe and continuous operation. Since early 2018, the unit has been in operation during the winter and experienced one failure in February 2019. Previously, heat had been supplied through electrical heaters, and a 16 kW air-to-water heat pump still in use during the summer. Effects from biochar use at the farm are still unclear, and therefore only the biochar C sequestration effect was accounted.

Data about the case were collected through interviews with the project manager and a farm employee in charge of running the pyrolysis unit, phone communication with the plant manufacturer. Two workshops were also organised at the farm (spring 2018, spring 2019).

The set of commodities relevant for this case were: wood pellets, biochar, electricity, and heat. The processes available were:

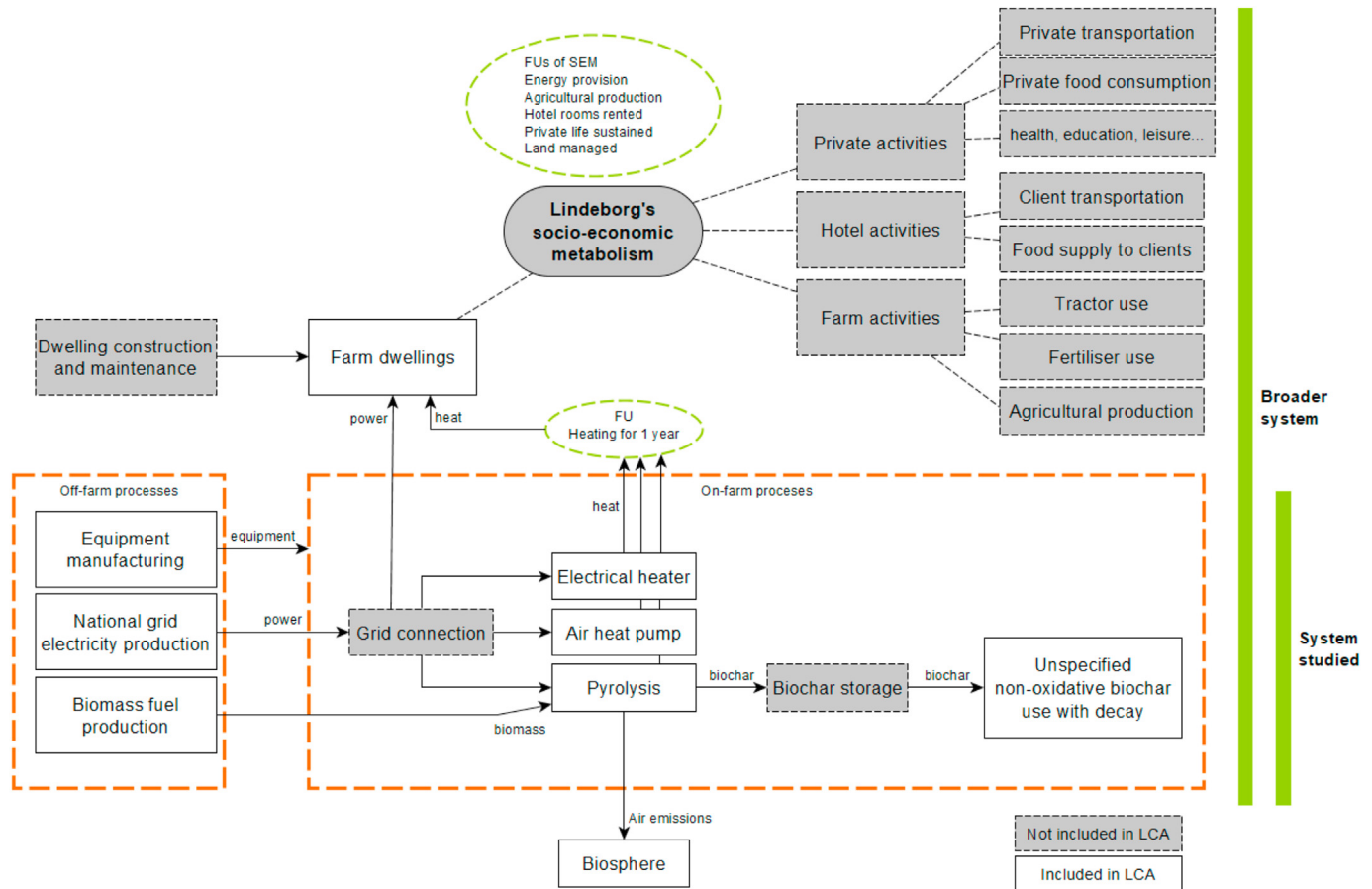
[3] https://www.lindeborgs.com/.

Fig. 2. The studied energy system in the broader picture of the farm's socio-economic metabolism. FU: Functional unit (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

wood pellet pyrolysis, air-to-water heat pump, electrical heating. For comparison with reference technologies, wood pellet combustion was also modelled (theoretical). The farm is equipped with water tanks that act as a daily buffer for the heat demand, but these tanks do not provide heat storage over more than several days. Therefore, no heat storage was modelled and the time scale of the model was set to daily averages. A year was defined as the time period from August, 1st, to July, 31st the following year. This was preferred over calendar years to avoid splitting winter seasons.

3.1.2. Energy demand

3.1.2.1. Current heat demand for space heating and hot water

The farm's heat demand is composed of space heating and hot water production. Since no metering data was available, heat demand time series were modelled. Total annual heat demand for a normal year was calculated using energy declarations for each building from the Swedish National Board of Housing, Building, and Planning (Boverket). For each building, a fixed share of that annual amount was allocated to hot water production (5−8%). The remainder represented space heating demand for a normal year. Conversion of space heating for a normal year to actual weather variations was made using the degree-day methodology (Spinoni et al., 2015) and hourly local temperature data from the Swedish Meteorological and Hydrological Institute (SMHI). Calculations were made hourly, before aggregation to daily averages.

Hourly heat demand was calculated as per Eq (8), where $T_{ext,t}$ is the outdoor temperature at time t, and T_h is the temperature above which no heating is needed (set to 17 °C in Swedish regulation), χ is the characteristic function for the set of temperature above the control temperature, and a is a parameter in kW K^{-1} representing the thermal properties and floor areas of the buildings.

$$d_{heat,t} = a \cdot (T_{ext,t} - T_h) \cdot \chi_{\{T_{ext,t} > T_h\}} \qquad (8)$$

The parameter a (Eq (9)) was estimated using historic temperature data from 1996 to 2010 (assumed to represent a normal year), the area of the buildings S_i in m^2, the energy performance of the buildings for a normal year E_i in kWh m^{-2} $year^{-1}$, and the share of hot water w_i. N is the number of years used for calibration (15) and t here is given in hours. The parameter a was equal to −1.7 kW K^{-1} (for 640 m^2 of heated space, i. e 2.6 W m^{-2} K^{-1}).

$$a = -1 \cdot \frac{N \cdot \sum_{i \in I} S_i \cdot E_i \cdot (1 - w_i)}{\sum_{t \in \mathscr{T}} (T_{ext,t} - T_h) \cdot \chi_{\{T_{ext,t} > T_h\}}} \qquad (9)$$

3.1.2.2. Future heat demand for space heating and hot water

Effects of climate change expected in Sweden were estimated using a simple method, for the years 2030−2048. Average

temperature increase per season in Sweden for the upcoming decades were taken from SMHI (Eklund et al., 2015). For the time period 2030−2048, these predictions do not differ much between emission pathways (RCP4.5 - Strong climate action; RCP8.5 − Business as usual). We accounted for the warming that has already happened in recent decades compared to pre-industrial levels by subtracting 0.5 °C to SMHI's prediction. The historic hourly temperature time series (2000−2018) were then modified, simplistically, by adding the following values to each season: +2 °C in winter (December−February); +1.5 °C in spring (March−May), +1.5 °C in summer (June−August), and +1.25 °C in fall (September−November). Seasons were defined as in (Eklund et al., 2015).

The heat demand was then recalculated for these modified temperature time series using Eq. (9). These constructed future time series take into account the expected average temperature increase (trend), but neglect any change in frequency and magnitude of extreme events (noise). Therefore, these future time series are to be seen as one simple stress test, among several possible, to explore what could happen to biochar-heating systems in upcoming decades, acknowledging that systems installed today are supposed to remain in operation for at least 20 years.

3.1.2.3. Heat demand for leisure greenhouse

In late 2019, Lindeborg started building a leisure greenhouse, adjacent to the pyrolysis unit. It will be made of two-sheet argon-filled glass (U = 1.1 W m^{-2} K^{-1}), have a floor area of 38 m^2, a total window surface of 113 m^2, and a volume of 153 m^3. The indoor target temperature will be 8 °C in winter. Assuming an air renewal rate of 1 vol per day, we calculated daily time series using equations similar to Eq (8), where a was the sum of two terms: thermal losses through the greenhouse's envelope and air renewal. Greenhouse heating lasted nearly 6 months and totalled 22 MW h year^{-1}.

3.1.2.4. Heat demand for grain drying

Grain drying was represented by a constant heat demand of 40 kW during 4 weeks in August−September. One MWh of heat was assumed to dry 7 tonnes of grain (dry basis, db), from moisture at harvest of 26% (db) down to 16% (db) for storage, with specific energy requirement of 1.5 kW h kg^{-1} water removed.

3.1.3. Energy supply

The energy conversion units available at the farm were: pyrolysis unit (50 kW heat), air-to-water heat pump (16 kW heat), and electrical heaters. For comparison with alternative reference systems, we also gathered data for a pellet combustion unit (50 kW heat).

Process data. The input and outputs ratios at full and part load for the various plants are given in Tables 2−4 in SI. Data about the pyrolysis process at full load were collected from interviews and an energy balance was performed to verify the information collected. In short, the pyrolysis plant has a 20% (dry weight) biochar yield, and liquids and gases are directly combusted, resulting in an energy yield of 55% at full load (% of the biomass LHV, 18.4 MJ/kg dry pellet).

Manufacturing. We assumed a lifetime of 20 years for all energy conversion units. In the life cycle, manufacturing of 50 kW units (regardless of pyrolysis or combustion) and heat pumps were represented by ecoinvent 3.5 processes. The manufacturing of small electrical heaters and heat distribution systems was not included.

Use-phase emissions. Since no data were available for the Bio-MaCon pyrolysis unit installed at the farm, proxy data were used. The proxy data came from a Pyreg unit installed in Högdalen,

Stockholm, for which a full-load performance test was performed in 2017 by the owner of the plant (see SI). The use-phase emission data included NMVOC (non-methane volatile organic compounds; non-fossil carbon monoxide, particulates (<2.5 μm) and nitrogen oxides. Since data for part load operation were not available, we assumed that at minimum load emissions would be 10% higher. Finally, for the alternative reference combustion process we assumed similar emissions per unit of biomass consumed (leading to lower emissions per unit of heat produced).

Constraints. The minimum operation time of any pyrolysis or combustion plant was set to 7 days. Heat pumps were turned off if pyrolysis or combustion units were running. This was based on management preferences at the studied farm.

Plant start-up and shutdown emissions. No start-up and shutdown emissions were included.

3.2. Simulation runs

Three simulations were run to highlight different features of on-farm biochar systems in Sweden.

3.2.1. (A) Biochar production potential and variability

In simulation A, the model was run for a series of past and future years. The goal was to estimate the variation in biochar production as a function of weather and climate variations, with the farm's current installation (i.e. 640 m^2 of heated space, pyrolysis of 50 kW, heat pump 16 kW, and electrical heaters). Plant flexibility and management were also analysed for the period 2000−2018 by changing minimum part-load and minimum operation time constraints.

Daily heat demand, with and without the effects of climate change in Sweden, was estimated using the method described in section 3.1, for the years 2000−2018 and for the years 2030−2048.

3.2.2. (B) Technology comparisons

In simulation B, the goal was to compare the environmental performance of 6 heating systems (B1-6, Table 2). System B1 and B2 had the same pyrolysis plant (50 kW), but B1 also had a heat pump. System B3 had a 30 kW pyrolysis plant and a heat pump. Systems B4-6 were reference technologies based on either a combustion plant, a ground source heat pump or electrical heaters. The year of study was set to 2017−2018.

Impact categories. For each scenario, life cycle inventories were compiled and life cycle impacts were calculated. The impact assessment included climate change impact (using IPCC, 2013; GWP$_{100}$) and all other 15 impact categories from the International Reference Life Cycle Data System (ILCD).

Sensitivity analysis. A sensitivity analysis of the climate change impact was performed for systems B1 and B2. The two factors analysed were the biochar stability and carbon intensity of

Table 2
Heating systems compared. Capacities given in kW heat.

System	Plants available	Short notation
B1	BioMaCon 50 kW; Heat pump 16 kW; Electrical heaters	PYR50 - HP - ELH
B2	BioMaCon 50 kW; Electrical heaters	PYR50 - ELH
B3	BioMaCon 30 kW; Heat pump 16 kW; Electrical heaters	PYR30 - HP - ELH
B4	Combustion 50 kW; Heat pump 16 kW; Electrical heaters	CMB50 - HP - ELH
B5	Ground source heat-pump 30 kW; Electrical heaters	GHP30 - ELH
B6	Electrical heaters	ELH
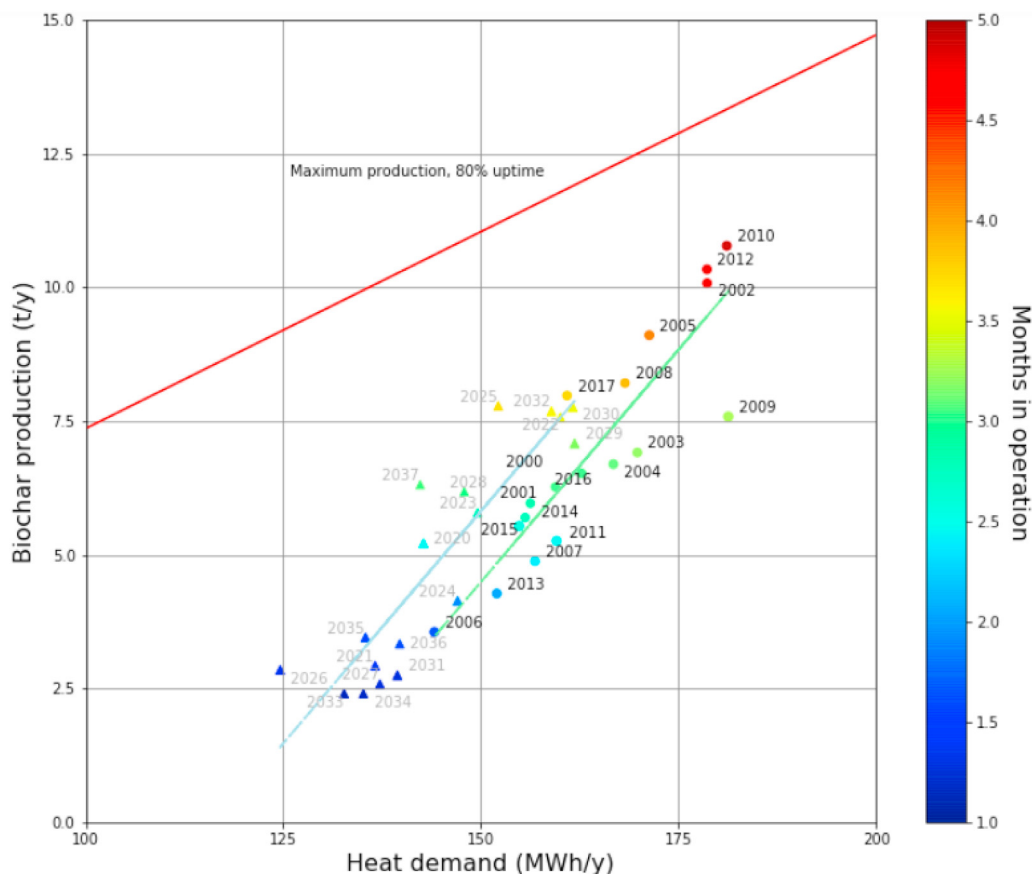
Fig. 3. Annual variability in biochar production potential at Lindeborg's farm equipped with a 50 kW pyrolysis plant, 2000–2018 (circles), and effect of climate change in 2020–2048 (triangles). Note: a year was defined as the time period from August, 1st, to July, 31st the following year.

electricity. For these parameters, the widest ranges of possible values are: 0%–100%, and 0–1200 g CO_2-eq kWh^{-1}, respectively.

3.2.3. (C) Heat demand expansions

The lifetime of a pyrolysis unit is expected to be about 20–30 years. During that time frame, the heat demand of the farm may change because of new activities. In simulation C, two ways of expanding the heat demand were analysed: building a 38-m^2 greenhouse (C1), and drying 175 tonnes (db) grain after harvest (C2). The goal was to investigate how the pyrolysis use could be optimised

and biochar production increased at Lindeborg's farm. The year of study was set to 2017–2018. Heat demand for the greenhouse (C1) and the grain dryer (C2) was calculated as described in section 3.1 and equalled 22 and 25 MW h year^{-1}, respectively.

4. Results

The general model was applied to one of the first Swedish farms equipped with a pyrolysis unit for heating and three simulations (A-C) were made.

Table 3
Biochar production, average pyrolysis load, operation time and process electricity for each plant, total heat demand, process electricity per unit of heating. Average and standard deviation values are given for an 18-year period. Current settings: default pyrolysis configuration; Plant management and flexibility: minimum operation time of 3 days; part load capacity of 30%. Climate change: increase in average winter temperatures of +2 with respect to 1960–1990 period.

Scenario	Current settings		Plant management and flexibility				Long-term climate change effect	
	2000–2017		2000–2017 Min-ops 3		2000–2017 Min-load 0.3		2020–2040 CC+2	
	Average	Std Dev	Average	Std Dev	Average	Std Dev	Average	Std Dev
Biochar production (Mg year−1)	6.98	2.10	7.94	1.77	10.9	1.04	4.90	2.12
Pyrolysis load (kW)	33.7	1.90	33.0	1.67	28.3	1.90	32.7	1.65
Operation time, pyrolysis (month year−1)	3.25	0.930	3.73	0.760	6.38	0.46	2.31	0.98
Operation time, heat pump (month year−1)	8.73	0.940	8.25	0.770	5.59	0.46	9.66	0.98
Operation time, electrical heater (month year−1)	8.81	0.900	8.33	0.720	5.68	0.44	9.70	0.96
Process electricity use, pyrolysis (MWh year−1)	5.69	1.71	6.47	1.44	8.90	0.85	3.99	1.73
Process electricity use, heat pump (MWh year−1)	16.6	2.73	15.2	2.27	7.64	1.42	17.6	2.79
Process electricity use, electrical heater (MWh year−1)	15.9	5.24	11.4	3.39	0.920	0.59	16.8	4.74
Total heat demand (MWh year−1)	164	10.8	164	10.8	164	10.8	145	10.9
Process electricity, total (MWh year−1)	38.2		33.1		17.5		38.4	
Process electricity per heat demand (MWh el MWh−1 heat)	0.232		0.201		0.106		0.265	

Table 4
Inputs and outputs for each heating alternative, for one year of heating (2017−2018, 161 MW h of heating). B1 = PYR50 - HP - ELH; B2 = PYR50 - ELH; B3 = PYR30 - HP - ELH; B4 = CMB50 - HP - ELH; B5 = GSHP30 - ELH; B6 = ELH.

Scenarios		Pyrolysis systems				References		Unit
		B1	B2	B3	B4	B5	B6	
Inputs	Wood pellet	39.4	39.4	48.2	21.6	−	−	t year^{-1}
	Total electricity	33.3	76.1	24.8	30.6	47.5	161	MWh year^{-1}
	Electricity for thermal plant	6.50	6.50	7.95	3.77	-	-	MWh year^{-1}
	Electricity for heat pump	13.8	-	5.87	13.8	10.9	-	MWh year^{-1}
	Electricity for electrical heater	13.0	69.6	11.0	13.0	36.6	161	MWh year^{-1}
Outputs	Heat demand	161	161	161	161	161	161	MWh year^{-1}
	Biochar	7.98	7.98	9.75	−	−	−	t year^{-1}
	Ashes (estimated)	−	−	−	0.647	−	−	t year^{-1}
Indicator	Electricity use per heat demand	0.207	0.473	0.154	0.190	0.295	1.00	MWh el MWh^{-1} heat

4.1. (A) Biochar production potential and variability

The unit commitment model was run for two periods of 18 years (2000−2018 and 2020−2038) under different model constraints in order to capture the effects of weather variability, plant management and flexibility, and long-term climate change. In all runs here, the farm was equipped with a 50 kW pyrolysis plant, a 16 kW air heat pump, and electrical heaters.

Weather variability. For years 2000−2018, the average biochar production potential was 7.0 tonnes year^{-1}, for an average heat demand of 161 MW h year^{-1} (Fig. 3). This corresponds to an average of 43 kg biochar MWh^{-1} of heating, or 11 kg biochar m^{-2} year^{-1} of heated area.

The biochar production potential varied linearly with the heat demand but also had some noise related to the weather variations. For a narrow heat demand interval, e.g. 175−180 MW h, the biochar production had a spread of up to 3.3 tonnes (Fig. 3). This was explained by the variation in length of the heating season (horizontal colour strata, Fig. 3).

In Fig. 3, several outliers can be noted. Winters 2009−2010 and 2010−2011, which were significantly cold winters for Sweden, had roughly the same annual heat demand. Still, the estimated biochar production differed greatly. On the other extreme, the 2006−2007 winter was a mild winter, described as an increasingly likely future winter under the effect of climate change in Sweden (Sweden facing climate change, 2007). Its biochar production potential was 49% below average.

Variations in biochar production or pyrolysis use were negatively correlated to consumption of electricity for heating, in both absolute (MWh year^{-1}) and intensive values (MWh electricity MWh^{-1} heat) (SI). The lowest pyrolysis use was associated with the highest electricity consumption, even during years with a lower heating demand than average.

Plant management and flexibility. For a 50 kW plant used with an 80% uptime rate, the maximum biochar production is 26 tonnes (i.e. 350 MW h of heat supplied by pyrolysis, at a constant ratio of 74 kg biochar MWh^{-1} heat). With the farm's current settings, average production was 73% lower. Beyond the fact that farm heat demand was lower than the plant's capacity, part of the gap is explained by (i) the plant's minimum operation time of 7 days, and (ii) the minimum load of 50% of its nominal capacity.

With a lower (i) minimum operation time constraint of 3 days, the biochar production was only 14% higher (+0.96 tonne). The pyrolysis plant was used 15% longer (+15 days) (Table 3).

Changing the (ii) minimum load from 50% to 30% led to a larger increase in biochar production (57%, +4.0 tonnes). The pyrolysis plant was used 96% longer (+95 days) (Table 3). The pyrolysis manufacturer disclosed that diminishing the minimum load down to 30% was possible with the plant studied, but that it would lead to

a reduced lifetime of the plant (due to e.g. fractures in insulation mantle, corrosion in reactor chamber).

Bridging the gap by heat demand expansion at the farm was explored in simulation C

Long-term climate change. The simulation of long-term climate change effects yielded an average biochar production potential that was 30% lower. The total amount of electricity consumed for heating remained similar, meaning that the farm's reliance on electricity for heating increased (Table 3).

4.2. (B) Technology comparison

Six heating systems were compared (B1-6, Table 2). The system boundaries included all upstream emissions, use phase emission, and an estimate of biochar C sequestration, but notably excluded any specific biochar use phase with remarkable agricultural benefits. Simulations were here run for a single year, 2017−2018.

Life cycle inventory. At the commodity level, the pyrolysis scenarios consumed up to twice as many wood pellets and more electricity than a conventional combustion plant. These scenarios produced however 6−8 tonnes of biochar (Table 5).

In all cases, electricity consumption remained 53%−80% lower than with pure electrical heating. Even if most of the heat is supplied by the pyrolysis/combustion plants (58%), running a heat pump running during the summer significantly reduces the electricity consumption (50%). This lower electricity consumption could also be achieved by other technologies, e. g solar thermal collectors.

Effect of the daily modelling time step on the electricity mix consumed. The main pyrolysis scenario (B1) consumed 33 MW h of electricity to run the heating system. This was split between the pyrolysis plant (19.6%), the heat pump (41.5%), and the electrical heater (38.9%) (Table 4). The pyrolysis plant consumed electricity produced mostly during winter months, while the heat pump operated in the summer. Electrical heating was used for a few hours to either supplement the heat pump or the main plant. This resulted in different apparent electricity mixes and emission factors: 53.9, 38.5, and 44.9 g CO_2 kWh^{-1}, respectively (Table 5). On average, this system consumed an apparent electricity of 44 g CO_2 kWh^{-1}, which was slightly higher than the Swedish annual average grid intensity of 42 g CO_2 kWh^{-1}, as calculated in our dataset for 2018.

Using the annual average electricity emission factor would have led to a small underestimation of the emissions (64.2 kg CO_2-eq), at least when using average data and in the case of Sweden, where nuclear and hydroelectricity dominate the electricity mix. This might be different in other world regions, or if short-term marginal data would have been used. See also the sensitivity analysis performed below (Fig. 5).

Life cycle impact assessment. The impact assessment included 15 ILCD impact categories and climate change using the IPCC 2013

Table 5
Carbon intensity of the electricity consumed by each plant in each scenario, given in gCO$_2$-eq kWh^{-1}. B1 = PYR50 - HP - ELH; B2 = PYR50 - ELH; B3 = PYR30 - HP - ELH; B4 = CMB50 - HP - ELH; B5 = GSHP30 - ELH; B6 = ELH.

Plant	B1	B2	B3	B4	B5	B6
Thermal plant	53.9	53.9	49.6	54.0	–	–
Heat pump	38.5	–	32.8	38.5	47.3	–
Electrical heater	44.9	39.7	55.7	44.9	55.8	47.8

method. For clarity, only four impact categories are presented below (climate change, land use, ozone layer depletion, and health respiratory effects); the others are available in SI.

Climate impact (Fig. 4a). All pyrolysis configurations had a better *net* climate score than the reference technologies. This was essentially due to the biochar C sequestration, without which the climate emissions of the pyrolysis scenarios would be higher than the reference scenarios.

Other impact categories revealed shifting of environmental burdens. The results are presented without any normalisation weights, and what is of interest is the relative difference between scenarios rather than the absolute values.

Reduced environmental impacts (Fig. 4b). Pyrolysis- and combustion-based heating had significantly lower potential ozone layer depletion impact than pure electrical heating. This was a direct consequence of the lower electricity consumption of these heating systems, and was also related to the high share of nuclear electricity in the Swedish mix.

Similar patterns were observed for 3 other impact categories: ionising radiations, dissipated water, and fossil resource depletion (see SI).

Increased environmental impacts (Fig. 4c–d). Pyrolysis-based heating had significantly higher land use and health respiratory impacts than combustion-based and pure electrical heating. This was essentially due to the higher throughput of biomass in these scenarios. For health respiratory effects, plant use phase emissions accounted for about a third of the impact.

This pattern was also the case for 10 other impact categories: freshwater and terrestrial acidification, freshwater eco-toxicity, freshwater eutrophication, marine eutrophication, terrestrial eutrophication, carcinogenic effects, non-carcinogenic effects, respiratory effects, photochemical ozone creation, and mineral and metal resource depletion (see SI).

Environmental hotspots and localisation of impacts. The major environmental hotspot in the pyrolysis systems was biomass fuel production, here assumed to be commercial wood pellets. The use phase emissions were also an important source of potential impacts. The use phase emissions represent a re-localisation of impacts on the farm, compared with electrical heating where emissions occur elsewhere.

Sensitivity analysis of the climate impact to two parameters: biochar stability and carbon intensity of the electricity grid. The net climate score of the pyrolysis systems B1 and B2 (with and without a complementary heat pump) varied between −10.3 and −11.9 tonnes CO$_2$-eq year^{-1}. This score is a function of multiple parameters, two of which are key: the 100-year biochar stability (BS) and the carbon intensity of the electricity grid (EF). For these parameters, the widest ranges of possible values are: 0%−100%, and 0−1200 g CO$_2$-eq kWh^{-1}, respectively. The sensitivity analysis performed in Fig. 5 shows the range of values for which the heating system can be qualified as "climate positive". The term "climate positive" is here understood as when the amount of C sequestered in biochar for 100 years is higher than the direct (i.e. not including indirect effects) greenhouse gas emissions from the farm's heating system, in which biochar production occurs.
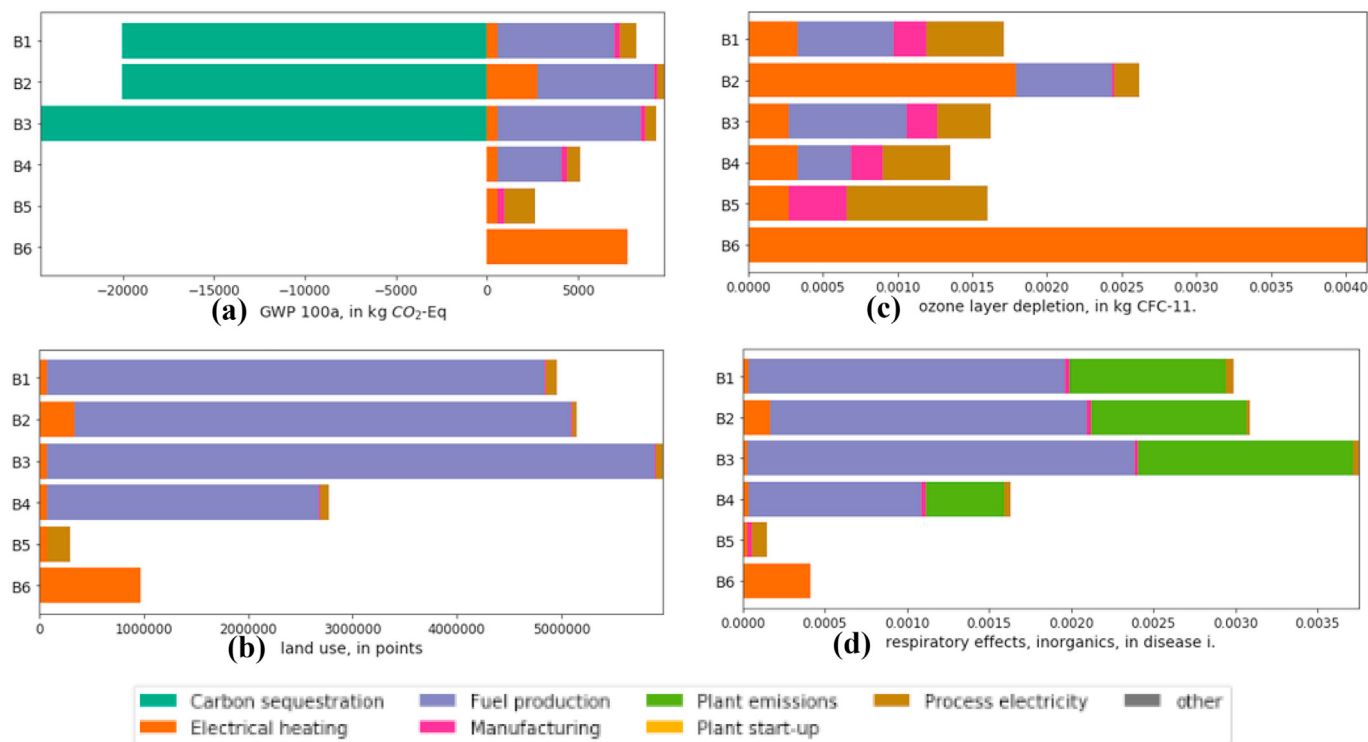
Fig. 4. Comparative LCA of farm heat supply for six scenarios. Impact categories presented here are (a) climate change, (b) land use, (c) ozone layer depletion, and (d) health respiratory effects. B1 = PYR50 - HP - ELH; B2 = PYR50 - ELH; B3 = PYR30 - HP - ELH; B4 = CMB50 - HP - ELH; B5 = GSHP30 - ELH; B6 = ELH. Other ILCD impact categories are compiled in SI (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)
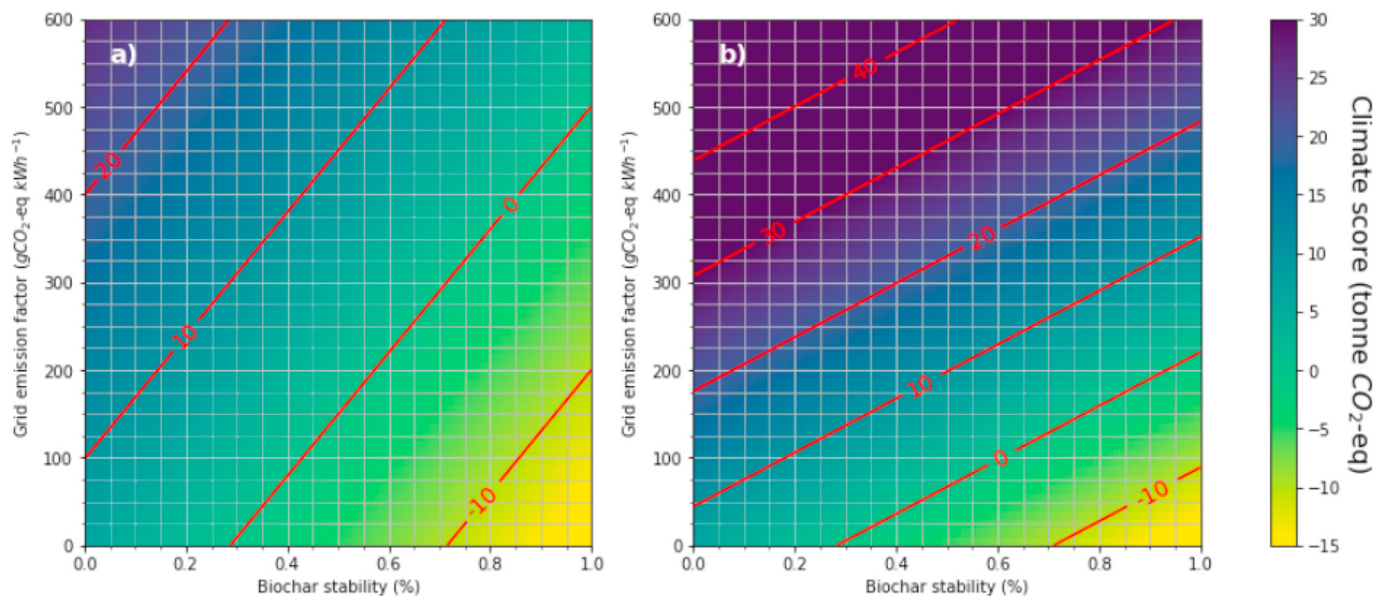
Fig. 5. Sensitivity of the climate score of the farm's biochar-energy system, (a) with heat pump and (b) without heat pump, with respect to carbon intensity of the electricity grid (EF) and biochar stability (BS). The climate change scores (CC) were here calculated with equation $CC = a + b \cdot BS + (c + d) \cdot EF$. Parameters a, b, c and d resulted from the heating systems modelled (a = emissions not affected by BS or EF; b = biochar production; c = electrical heating; d = heat pump electricity). The isocurve 0 indicates when the amount of C sequestered in the biochar is equal to the amount of greenhouse gases emitted by the heating system that produced the biochar (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

To be climate positive, the heating system must be in the lower-right corner of Fig. 5, that is, high stability and low grid emission factor. The slope of the iso-curves was about four times higher when a heat pump was available. This is a direct consequence of the coefficient of performance ($COP \approx 4$) of the heat pump.

Below 30% of biochar stability, the heating system could not be qualified as climate positive. Fortunately, with today's knowledge, biochar stability across all ranges of feedstock and production conditions is usually estimated at around 60%−90% (IPCC, 2019). With a heat pump, this biochar stability range required the electricity emission factor to be well below 200−500 g CO_2-eq kWh^{-1} (Fig. 5a). Without a heat pump, the requirement is more stringent: well below 100−200 g CO_2-eq kWh^{-1} (Fig. 5b). In Sweden, yearly average consumption electricity was estimated to be around 42 g CO_2-eq kWh^{-1}, with small intra-annual variations (20−90 g CO_2-eq kWh^{-1}).

4.3. (C) Heat demand expansions

Consecutive expansions of the farm's heat demand were modelled, starting from the existing buildings through (C1) a leisure greenhouse (construction in progress in 2019), and (C2) a grain dryer (theoretical). The biochar production increased from 7.0 to 9.7 and 12.4 tonne year^{-1}, but remained far from the maximum potential of the 50 kW pyrolysis plant (26 tonne year^{-1}, Fig. 6). Expanding the heat demand led to an increase in the share of heat supplied by the pyrolysis plant and its uptime. The output of the unit commitment model revealed that during very cold days, the additional heat demand from the greenhouse could push the system to consume more electricity (i.e. demand higher than plant capacity). This was less likely to happen with the grain dryer since the additional heat demand was consumed in the summer (SI).

The maximum production capacity can be reached by installing fans for heat dumping. This, despite not being resource efficient, can be considered if there is a demand for waste treatment, e.g. rotten silage not suitable for animal feed. In that case, the system also provides a waste treatment function (which is to be compared with other treatment options, e.g. landfilling, biogas).

5. Discussion

This section is split into two parts, discussing first on-farm biochar production, and then environmental modelling.

5.1. About on-farm biochar-energy systems

To the extent possible, we aim here to generalise the results from Lindeborg's case.

5.1.1. Coproduction of heat and biochar

In Lindeborg's case, biochar production was constrained by heat demand. Year to year variations in biochar production were primarily explained by weather. Another factor that affected the variations in biochar production was the dimensioning and the flexibility of the pyrolysis plant. The pyrolysis plant was oversized, i.e. it operated below its nominal capacity for most of the time or even near its shutdown capacity, which required more time to manage, emitted more air pollutants, and was less profitable. Oversized plants are also more sensitive to decreases in heat demand, such as the ones likely to be induced by climate change in Sweden. An undersized pyrolysis plant, i.e. operating at its nominal capacity most of the time but not providing all the heat demand, would instead be a missed opportunity to produce biochar with energy recovery. In small-scale systems, proper dimensioning of the pyrolysis plant is a key to success. Care must be taken to explore current needs but also future possible developments. Our tool allows for such modelling and can provide information for discussions with project owners, making efficient use of manufactured capital and investments.

5.1.2. Climate-positive heating in the farm's broader metabolism

Lindeborg's plant is one of the first on-farm pyrolysis plants in Sweden that received governmental funding under the title: climate-positive heating. The climate impact of the pyrolysis-based heating systems assessed here was dominated by the biochar carbon sequestration term, making the net score climate-positive
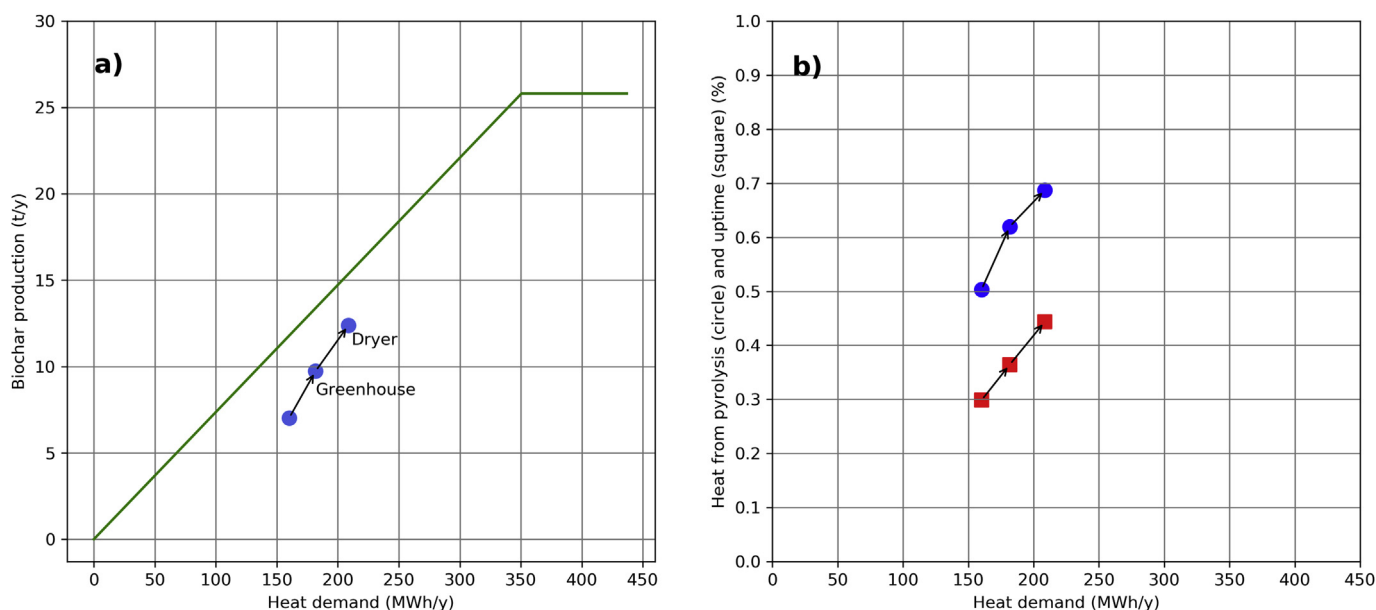
Fig. 6. (a) Biochar production potential (tonne year^{-1}), (b) heat supplied by pyrolysis (circle, % annual heat demand) and pyrolysis uptime (square, % of year), following successive expansions of heat demand (by building a greenhouse, and then a grain dryer). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

(Fig. 4). This outcome is possible thanks to the integration of the pyrolysis plant in a heating system made of numerous components (water tanks, insulated pipes, peak-electrical heaters, heat pump). In particular, the presence of a heat pump significantly affected the amount of electricity needed for heating and lowered the requirement on decarbonisation of the consumed electricity (Fig. 5). The complementarity between pyrolysis and another heat source could be obtained with other technologies, e.g. solar thermal energy.

Climate-positive heating is also a subtle concept. During cold winters, heat demand and therefore biochar production are particularly high. This makes the climate impact of pyrolysis heating even more beneficial than its conventional alternatives, when a non-intensive functional unit is used (e.g. heating for a year). Likewise, less-insulated buildings consume more heat per floor area. In fact, in the studied case, the two older buildings represent only 40% of the heated area but 60% of the heating demand. If expressed per heated area, the climate-impact of better-insulated houses would appear worse than the one of heat-leaking buildings, because less biochar is produced. Consequently, *net negative* climate change impacts for heating (Fig. 4) must be interpreted carefully and are at least partially an artefact of system boundaries.

We estimated the amount of biochar produced by the farm for its heating needs to be around 8 tonnes year^{-1}, which is about 20 tonnes CO_2-eq year^{-1} sequestered for more than 100 years. Producing that amount of biochar led to greenhouse gas emissions of about 8 tonnes CO_2-eq year^{-1} (Fig. 4). The remaining net CDR, 12 tonnes CO_2-eq year^{-1}, is roughly equal to the annual greenhouse gas emissions of 1.5 average Swedish citizen (Naturvårdsverket, 2019). The remaining net CDR can also be put in perspective using the broader socio-economic metabolism of the farm-hotel (Fig. 2), from which the need for heating arises. Estimates of diesel use for tractor, transportation of hotel guests, and some private transportation together equal to about 10 tonnes CO_2-eq year^{-1} (SI). When considering the broader organisation, as in organisational LCA (Martínez-Blanco et al., 2015), the notion of 'climate-positive' system fades away. What remains, and matters

for climate, is that direct greenhouse gas emissions are lower in the case of pyrolysis than with other technologies and that carbon dioxide removal is achieved.

5.1.3. Environmental burden of biochar carbon sequestration

In simulation B, we stressed that biochar carbon sequestration came at an extra environmental cost linked to the increased throughput of biomass. The biomass throughput is increasing impacts through three ways: (i) upstream, technosphere inputs are consumed to produce the biomass; (ii) upstream, more land is used to produce the biomass; and (iii) on-farm, more biomass is processed, with higher use phase emissions.

Lowering technosphere and land requirements. Lindeborg farm chose wood pellet for a safe and continuous operation of the pyrolysis plant. The initial plan was however to use biomass produced on marginal land and prunings. Sourcing the biomass locally may lead to less transportation and processing than using pelletized biomass. However, the fuel properties being different, the pyrolysis process would be affected.

Emissions during pyrolysis. Emissions of air pollutants during pyrolysis were included in the assessment with proxy data from a Stockholm pilot plant, and contributed significantly to human health impacts (Fig. 4). Concerns about emissions exist on the farmer's side, as was revealed during stakeholder interaction. However, no funds are currently available for monitoring of emissions from plant operation.

Importance of the biochar use phase. The biochar use phase modelled here only included the effect of biochar C sequestration. Biochar co-benefits, which are often cited by practitioners but rarely monitored, must be sought and obtained. This is, as far as we know, not yet the case in the studied farm, mainly because biochar use in organic farming was not allowed as of 2019 (Official Journal of the European Union, 2019). Co-benefits could compensate for the impacts of increased biomass consumption in the foreground system. They can be of three types: (i) changes in technosphere inputs to the farm (e.g. reduced use of mineral fertilisers, reduced irrigation (Fischer et al., 2018), reduced use of machinery); (ii) changes in the technosphere outputs from the farm (e.g. increased agricultural

production (Jeffery et al., 2017)); and (iii) direct land use or biosphere changes (e.g. soil emissions (Cayuela et al., 2014), soil nutrient leaching (Borchard et al., 2019), animal emissions (Kammann et al., 2017)). Co-benefits are needed for biochar to provide climate change mitigation in the short term (Woolf et al., 2010).

5.1.4. Integration of pyrolysis in the agricultural landscape

The case study focused on a single farm, isolated from the surrounding landscape. The farm's biochar production may increase with future developments (e.g. greenhouse, grain drying, new buildings, and aquaculture) and the farm expects to sell part of its biochar production to others. This raises the question of the integration of pyrolysis plants in an agricultural landscape: should each farm produce its own biochar (i.e. replicate the current case), or should there be some degree of centralisation?

Replicates of on-farm biochar-pyrolysis heating. In Sweden, there are about 60 000 agricultural holdings, of which 25000 have an arable land area between 5 and 20 ha (same size category as the studied farm) (Statistics Sweden, 2017). If in the coming years half of these farms were to replace their heating technologies by existing pyrolysis ones, it would lead to a biochar production of about 125000 tonnes year^{-1}. This order of magnitude is equivalent to 1 or 2 large-scale pyrolysis plants as envisioned in cities like Stockholm (Azzi et al., 2019). In terms of CDR, it would equal about 0.3 million tonnes of CO_2, that is 57% of Sweden's 2018 greenhouse gas emissions from working machinery in agriculture (excluding forestry) (Swedish Environmetal Protection Agency, 2019). Incentives for renewal of heating equipment should first target farms still relying on fossil fuels, in areas with a local-oversupply of biomass (and a need for biochar), and not exclude other renovation works like insulation. If desirable, this means large investment in manufactured capital (>€1 billion), maintenance, and consulting services, costs which have to be compared with other heating solutions. Similar on-farm pyrolysis heating systems are relevant in other countries with cold climates.

Biochar production at larger scales. A key factor in that discussion is technological. Large-scale pyrolysis plants are not yet available on the Swedish market and the available ones convert the pyrolytic gases and tars to heat, a low-exergy product. If plants that convert the pyrolytic gases and tars to high-exergy products like biofuel or electricity become commercially available, then it might be relevant to centralise biochar production around hubs in the agricultural landscape: industrial symbiosis with biogas plants can be considered (Salman et al., 2017) and a larger palette of biochar post-processing techniques would be possible (Mood et al., 2020) compared with on-farm production. However, the success of technological innovation in the agricultural landscape is subject to many factors, as shown with biogas technologies in Swedish agriculture (Karlsson et al., 2018).

The value of the niche. The challenges, limitations, and contradictions discussed above highlight that on-farm heating-biochar systems are evolving in a niche market. The niche currently benefits from the availability of capital investments, biomass, and supportive actors. But the niche is not without value: these pioneer-biochar projects contribute to market development, social and technological learning.

5.2. About the model developed

5.2.1. LCA, model integration and reusability

The model developed in this paper combined dynamic modelling of farm energy systems with life cycle assessment (LCA). Traditionally, these two types of modelling have belonged to different communities. Combining them, however, allows for some

of the complexity of real systems to be reflected in LCA results (e.g. detailed emission factor for electricity, and efficiencies and emissions at part-load). By mainstreaming LCA integration to other fields, LCA could be performed earlier in project development and, hopefully, lead to more impactful LCA results. This mainstreaming of LCA is happening also in other fields, e.g. construction industry and planning (Francart et al., 2019) or chemical process development (Joyce et al., 2018). In addition, the LCA inventory generated by the model can be edited in conventional LCA software for further analysis and modelling. This transition is greatly enabled by the flexibility of programming languages like Python, code-sharing platforms, and for LCA, the availability of an open-source framework (Mutel, 2017).

The model is made available online and is intended to be used by others, e.g. researchers and consultants. It can be applied to larger farms with different energy demand profiles or equipped with different technologies, or to model how a pyrolysis plant can be integrated into any existing energy system (e.g. farms, small neighbourhoods, or industries). Additional features can easily be added to provide a more comprehensive assessment of the farm's metabolism. In particular, vehicle and machinery fuel consumption could be added or distinctions could be made between different heat qualities (e.g. hot water at 90 °C for space heating, waste heat at 40 °C recovered for greenhouse heating). While we did not perform economic calculations, the features remain available as in the original *ficus* library (Atabay, 2017).

5.2.2. Data gaps and model limitations

The model's main sources of uncertainty are (i) the heat demand estimates, (ii) the plant data, and (iii) the representativeness of the model's constraints to reality.

Determination of the buildings' thermal properties was made using energy declarations for normal years. Then instant heat demand was estimated using a well-established method, degree-days with hourly temperature data (Spinoni et al., 2015). Performing these estimates was motivated by the lack of long time series from the case study. More validation data are however expected in the coming years, with monitored electricity and pellet consumption.

Pyrolysis plant data includes commodity input and output ratios, part load efficiencies, and environmental emissions. Some data were collected via discussion with the plant owner and manufacturer. However only rough information was available, and no data on emissions were directly available. Part-load efficiencies and emissions were not available. There is a need to perform emission tests of these new pyrolysis plants, as has been done for other technologies by the Swedish Energy Agency. In particular, the tests performed for pellet combustion boilers included emissions of air pollutants at both nominal capacity and part load capacity.[4]

Finally, we added two constraints to the energy system model following discussion with farmers: exclusive processes and minimum operation times (see section 2.1.4). These constraints affected which plant the model would decide to run. A few times, this led to shutdowns of the pyrolysis plant for short periods of time because of a single day with high outdoor temperature. The reality of such situations could only partly be verified by discussion with another farmer who experienced automatic shutdown on warm days. These situations do not affect the biochar production estimates significantly, however, they could influence the emissions of air pollutants during start-up and shutdown of plants. From that perspective, the model can be refined by adding two types of start-up (cold and warm), and constraining load variations (ramp constraint). Validation of the model realism could be easily made by careful

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[4] https://www.energimyndigheten.se/tester/.

observation of the plant's operation time, number of start-ups and shutdown.

5.2.3. Towards using real-time electricity data in LCA

Climate change impact from electricity. The case study was analysed at a daily time scale. This allowed us to capture variations in the electricity mix consumed by the farm's heating system (Table 5), which is usually not performed in LCA studies. In winter, when the pyrolysis was in operation, the calculated carbon intensity of the grid was slightly higher than in summer when the heat pump was in operation. As shown in the sensitivity analysis, not taking into account these daily variations, and applying instead a constant emission factor for consumed electricity, would have led to a small underestimation of the climate impact (Fig. 5). The increased level of detail of the model did not dramatically change the results. The main reason is that average data was used in a country where the electricity mix is dominated by two low-carbon electricity sources (nuclear and hydroelectricity). This could have been different in regions where electricity generation is more diverse and volatile, but also if marginal data had been used instead of average data. There are various models for marginal electricity in Europe (short- and long-term) with different rationales and purposes (Ryan et al., 2016). A pragmatic alternative to making a modelling choice is to perform a complete sensitivity analysis on the electricity parameter, as shown in Fig. 5, and derive general conclusions on the requirement of electricity decarbonisation. This requirement for a biochar system to be climate-positive, however, does not tell us whether our global society has enough resources to consistently supply electricity below that threshold while also meeting all other human needs.

Environmental impacts from electricity. Time series of electricity mixes, such as the ones provided by national energy agencies or as compiled from these agencies by Electricity Map,[5] provide the composition of the electricity mix at any given point in time. With these time series, only the carbon intensity of the electricity is usually computed. However, to perform a complete LCA (i.e. including all environmental impact categories), this is not sufficient. The LCA database Ecoinvent (Weidema et al., 2013) provides complete life cycle inventories (LCI), but its market processes for national grid mixes are usually given as annual averages and the underlying assumptions that generate various system-models are not easily changeable (Cox et al., 2018). In this paper, to keep the LCA complete and at a high time resolution, we combined hourly production data in Sweden with Ecoinvent processes for each technology represented in the Swedish mix. This required a correspondence table because the two data sources did not share the same classification (see SI).

Relevance of increased computational cost. Such refinements come at an increased computational cost. Our climate impact results were not significantly affected by the increased accuracy compared with annual average data. This may question the usefulness of using real-time data for electricity mixes in situations where electricity load shifting is not modelled.

6. Conclusions

A model was developed to assess biochar production in small-scale on-farm energy systems. The model is available online and can be re-used by consultants and researchers alike. It was applied to one case study, Lindeborg Farm, focusing on its biochar production potential and LCA of its heat supply.

The farm's average biochar production potential was estimated to be 7.0 ± 2.1 tonnes year^{-1}. Estimated climate change in Sweden

over the period 2030−2050 was estimated to reduce that potential by 30% in the current configuration. The climate change impact of on-farm pyrolysis heating was lower than that of alternative solutions such as electrical heating or combustion, but only because of the carbon sequestered in biochar. Environmental impacts such as human respiratory diseases and terrestrial eutrophication increased, due to higher consumption of wood pellets and pyrolysis emissions. Biomass production was an environmental hotspot in the heating system. Sourcing part of the biomass required from available on-farm residues or agricultural wastes may reduce this impact. The pyrolysis plant can be used more efficiently by expanding the heat demand of the case farm. Heating a greenhouse and drying grain with the pyrolysis plant would produce +2.4 and + 3.0 additional tonnes of biochar. Overall, the farm's heating system achieved net carbon dioxide removal through biochar carbon sequestration, but this came at an environmental cost caused by increased biomass use. In future, it is crucial that expected co-benefits from biochar use in agriculture are realised.

Today's 'climate-positive heating' through biochar production is likely to be a niche that will bring technological learning to the biochar sector. As new biochar projects develop and the sector matures, adaptable and re-useable modelling tools will be relevant.

CRediT authorship contribution statement

Elias S. Azzi: Conceptualization, Methodology, Software, Writing - original draft. **Erik Karltun:** Conceptualization, Writing - review & editing. **Cecilia Sundberg:** Conceptualization, Writing - review & editing, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2020.124873.

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[5] https://github.com/tmrowco/electricitymap-contrib.

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