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1 Climate impact and energy efficiency from electricity
2 generation through anaerobic digestion or direct
3 combustion of short rotation coppice willow

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8 **Abstract**

9 Short rotation coppice willow is an energy crop used in Sweden to produce elec-
10 tricity and heat in combined heat and power plants. Recent laboratory-scale ex-
11 periments have shown that SRC willow can also be used for biogas production in
12 anaerobic digestion processes.

13 Here, life cycle assessment is used to compare the climate impact and en-
14 ergy efficiency of electricity and heat generated by these measures. All energy
15 inputs and greenhouse gas emissions, including soil organic carbon fluxes were
16 included in the life cycle assessment. The climate impact was determined using
17 time-dependent life cycle assessment methodology.

18 Both systems showed a positive net energy balance, but the direct combustion
19 system delivered nine-fold more energy than the biogas system. Both systems had
20 a cooling effect on the global mean surface temperature change. The cooling

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21 impact per hectare from the biogas system was nine-fold higher due to the carbon
22 returned to soil with the digestate.

23 Compensating the lower energy production of the biogas system with external
24 energy sources had a large impact on the result, effectively determining whether
25 the biogas scenario had a net warming or cooling contribution to the global mean
26 temperature change per kWh of electricity. In all cases, the contribution to global
27 warming was lowered by the inclusion of willow in the energy system. The use
28 of time-dependent climate impact methodology shows that extended use of short
29 rotation coppice willow can contribute to counteract global warming.

30 *Keywords:*

31 Land use change, Soil carbon, Life cycle assessment, Time-dependent climate
32 impact, Biogas, Combined heat and power

33 **Glossary**

34 ΔT_S	Global mean temperature change
35 C	Carbon
36 CH ₄	Methane
37 CHP	Combined Heat and Power
38 CO ₂	Carbon dioxide
39 DM	Dry Matter
40 ER	Energy Ratio
41 GHG	Greenhouse gas
42 GWP	Global Warming Potential
43 HHV	Higher Heating Value
44 HRT	Hydraulic Retention Time
45 ICBM	Introductory Carbon Balance Model
46 iLUC	indirect Land Use Change

47	LHV	Lower Heating Value
48	LCA	Life Cycle Assessment
49	MC	Moisture Content
50	N ₂ O	Nitrous Oxide
51	OLR	Organic Loading Rate
52	SOC	Soil Organic Carbon
53	SRC	Short rotation coppice
54	VS	Volatile Solids

55 **1. Introduction**

56 In order to decrease the climate impact from the European power sector, it
57 is important to increase the share of renewable sources in the European power
58 supply. Bioenergy is an important resource in the Swedish energy system making
59 up 40 % of the energy input in 2011 [1]. Bioenergy is frequently used in combined
60 heat and power (CHP) applications, for which the Swedish forest industry is the
61 largest supplier of biomass. In this study the effects on climate impact from heat
62 and power generation using biomass from the agricultural sector were studied.

63 Short rotation coppice (SRC) willow is a well-established woody energy crop
64 that has received particular attention over the last 30 years for its high potential dry
65 matter (DM) yield and suitability for use in conventional CHP plants. It is often
66 used for co-firing with other feedstock in large- or medium-scale CHP plants.

67 An alternative way of generating electricity and heat is through gas engines.
68 For instance, the majority of the biogas produced in Germany is used in small-
69 scale CHP units that feed into the electricity grid. Farm-scale biogas is still a
70 marginal bioenergy producer in Sweden [2]. It does however have a large poten-
71 tial, especially if manure and energy crops are used as feedstock for the digestion
72 process [3]. Digesting manure alone in an anaerobic digestion process is expen-
73 sive due to its high water content which lowers the effective output per unit volume
74 of the digester. One way of increasing the output of the digester is to increase the
75 DM and carbon (C) content of the substrate by co-digestion with a drier substrate
76 [4].

77 Converting biomass to biogas enables the recycling of nutrients and C back
78 to the field with the digestate, which can affect the soil organic carbon (SOC)
79 levels [5, 6], and, ultimately, the climate impact of the electricity generated. To
80 our knowledge, no studies have been published quantifying how large this impact
81 on the climate might be relative to those from the other parts of the bioenergy
82 production system and how it may vary over time.

83 When evaluating the climate impact of electricity generated from biomass, one
84 has to consider both greenhouse gas (GHG) emissions and the energy efficiency of
85 the system used to generate the electricity. Life cycle assessment (LCA) method-
86 ology [7, 8] is commonly used to achieve this. Several authors have investigated
87 the energy efficiency and greenhouse gas emissions from electricity generating
88 systems using SRC willow as feedstock [9, 10, 11, 12, 13, 14, 15, 16]. Energy
89 production from other SRC crops, such as poplar [17] and eucalyptus [18], have
90 also been studied from a life cycle perspective. These can be cropped similar to
91 SRC willow and often show similar energy and GHG performances [19, 18]. Sev-
92 eral studies have considered SOC changes when estimating the climate impact
93 from SRC systems [11, 20, 13, 14, 16, 21]. We are however not aware of any pub-
94 lished LCA studies investigating the importance of timing of emissions in SRC
95 willow systems and the effects of the digestate on SOC changes.

96 The most common way of characterizing the climate impact in LCA is to de-
97 termine the global warming potential (GWP) [22]. However, this metric has been
98 criticized, among other things, for not being able to capture the climate effects of
99 C stock changes in biomass used for bioenergy when the life cycle net C balance
100 is zero [23, 24]. When a land use change occurs, the impacts on climate may also
101 change over time due to SOC dynamics [25, 26]. The inclusion of soil carbon
102 changes and timing of GHG emissions in bioenergy LCA's of electricity and heat
103 generation has been argued for in order to avoid false assumptions about the long
104 and short term climate impact [27]. To capture and interpret these dynamic effects
105 in an LCA is a challenge that requires a different impact indicator [28]. One such
106 indicator is the global mean surface temperature change (ΔT_S) [29, 16], which was
107 used in this study.

108 The aim of this study was to compare the energy efficiency and climate impact
109 of two ways of generating electricity and heat from SRC willow. The two energy
110 conversion pathways investigated were 1) direct combustion in a central CHP
111 plant and 2) conversion of the willow feedstock to biogas through co-digestion
112 with liquid manure before burning the biogas in a small scale gas engine CHP. A
113 trade-off between energy production and carbon sequestration similar to that of
114 biochar systems [30] was expected. This paper serves the dual purpose of quan-

115 tifying the time-dependent climate impact of different bioenergy systems as well
116 as studying the trade-off between energy generation and climate impact mitiga-
117 tion through carbon sequestration that can be expected in the biogas scenario as
118 digestate is added to the soil.

119 **2. Methodology**

120 Life cycle assessment methodology was used to assess the climate impact and
121 effect on the energy efficiency from all relevant GHG and energy flows taking
122 place throughout all life cycle stages of electricity and heat generation [7, 8].
123 The study took the form of a comparative LCA with a cradle-to-gate perspective,
124 starting with the extraction of resources and ending with delivery of the electricity
125 generated to the grid. The timing of GHG fluxes was determined to assess the
126 time-dependent climate impact [16](see section 2.7).

127 A model of a bioenergy production system using willow established on fallow
128 land was set up. A dairy farm with 300 cows and with existing infrastructure for
129 anaerobic digestion of the liquid manure and generation of electricity and heat
130 from the biogas was assumed. Emissions and energy requirements related to con-
131 struction and decommissioning of the infrastructure was excluded from the LCA for
132 both scenarios.

133 In the biogas scenario, the willow was used within the current infrastructure
134 on the farm, i.e. the willow biomass was co-digested with manure in the anaerobic
135 digester and the biogas was combusted in a gas engine to generate electricity and
136 heat (Fig. 1). In the direct combustion scenario the willow biomass was trans-
137 ported to a central CHP plant and incinerated in a furnace to generate electricity
138 and heat. In both scenarios the electricity generated was fed into the Swedish
139 electricity grid and the recoverable heat was delivered to local DH distribution
140 systems.

141 *2.1. System boundaries and general assumptions*

142 The production of inputs, cultivation and harvest of willow, storage losses,
143 transportation of biomass to the conversion facility, preparation of the biomass to
144 be converted and return of the residues to the field were all included within the
145 system boundaries (Fig. 1). Activities and losses taking place after the delivery
146 of the electricity and heat, such as distribution losses, were outside of the system
147 boundaries. The energy and mass flows affected by the introduction of the willow
148 system in the biogas process at the dairy farm were included. Other activities on
149 the dairy farm were outside the system boundaries.

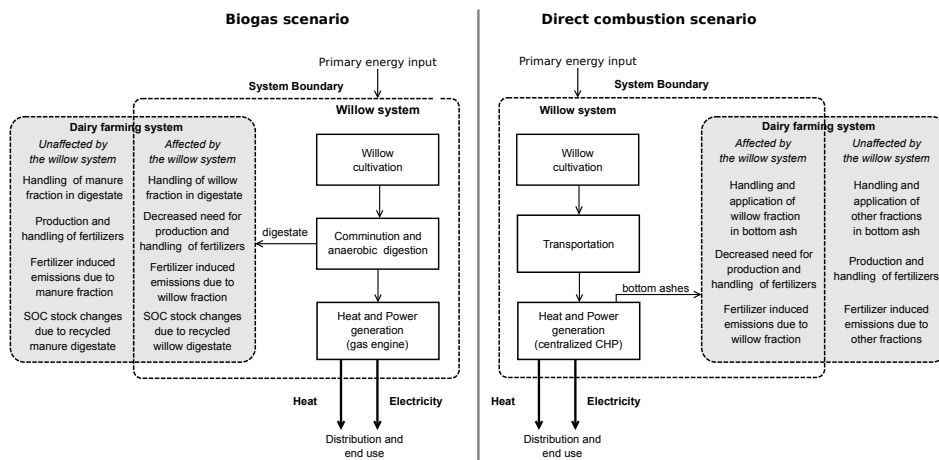


Fig. 1. System boundaries of the scenarios used in this study. Greenhouse gas fluxes in the dairy system resulting from the introduction of the willow system on the farm were included within the system boundaries.

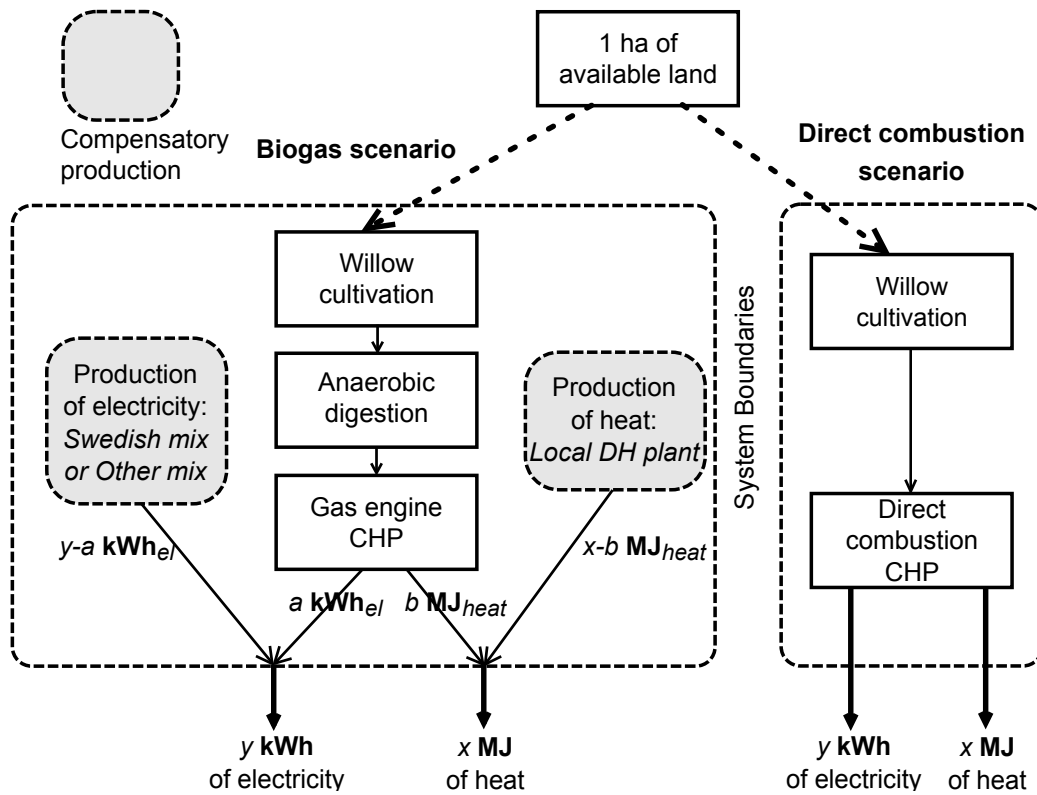


Fig. 2. Adjustment of the reference flow of the biogas system to give equal output in both scenarios. External production of heat and electricity was added to the biogas scenario. The magnitude of the reference flow in the direct combustion scenario was determined by the amount of land available for willow production.

150 All energy and GHG fluxes were recorded in a time-distributed life cycle in-
151 ventory [16] as individual net emission impulses with a time resolution of one
152 year. All upstream activities were accounted for in the year in which the activity
153 that gave rise to them occurred. The fluxes of the three major GHG contributing to
154 global warming, carbon dioxide (CO₂), methane (CH₄) and nitrous oxide (N₂O),
155 were determined for both scenarios.

156 Results were calculated on a per hectare basis for heat and electricity and
157 converted to per kWh of electricity delivered. The climate impact was calculated
158 as global mean surface temperature change (ΔT_S) per kWh of electricity delivered
159 by dividing the temperature effect for each year by the expected total output of
160 electricity to the grid from each of the two scenarios. This restricted the validity
161 of the interpretation to the average climate impact of two full rotations of willow.

162 Allocation of emissions and primary energy was done using the alternative
163 generation method [31], also known as the efficiency method [32]. Harmonized
164 reference values [33, 34] for the separate production of electricity and heat from
165 biogas and wood fuel were used for the two scenarios. Total emissions and pri-
166 mary energy allocation factor for electricity used in the biogas and direct combus-
167 tion scenarios was 0.60 and 0.54, respectively.

168 2.2. System description

169 2.2.1. Common characteristics

170 Mean annual temperature at the willow plantation was 5.5 °C and mean annual
171 precipitation 600 mm. The soil was a typical clay soil. The study period covered
172 two subsequent SRC willow rotations, spanning 25 years each. The coppicing
173 cycle was 3 years. The first harvest of each rotation yielded two-thirds of the
174 harvest at full capacity, which was 30 t of DM per ha (10 t of DM per (ha yr)).

175 To ensure a constant supply of willow to the biogas process, one-third of the
176 total area needed was established each year over a period of three years. The
177 willow contributed a 50 % share of the volatile solids (VS) to the substrate mixture
178 entering the anaerobic digestion process.

179 The management of the willow plantation followed established guidelines
180 [35], such as soil preparation in year 0, mechanical weed control, planting, ap-
181 plication of pesticides, fertilization and harvesting, and cutting up the roots and
182 stools in spring after the last harvest of each rotation. Harvest took place in winter
183 using a whole stem harvester. Delivery to the biogas plant or direct combustion
184 CHP took place continuously. Stems were stored at the field side until delivery.
185 The stems were chipped before transportation using a mobile wood chipper. The

186 wood chips were then loaded on container trucks. Each truck carried 36 t of wet
187 biomass [36] and had an empty return trip to the field.

188 2.2.2. *Biogas scenario*

189 At the biogas plant, the willow chips were comminuted to a particle geometric
190 length of 2 mm before being mixed with the liquid manure and pumped into the
191 digester.

192 Electricity and heat were generated in a gas engine and 20 % of the heat gen-
193 erated [37] and 8 % of the electricity [38] were used for heating and operating the
194 biogas process and CHP auxiliary equipment. An additional 15 % of the generated
195 heat was lost in the form of low-grade heat which could not be recovered for DH
196 purposes [37]. The specific energy needed for comminution of the biomass was
197 calculated to be 79 kWh per t of DM [39]. This represented an additional internal
198 energy consumption of 23 % of the generated electricity in the biogas scenario.
199 The remaining 68 % of the electricity and 65 % of the heat generated were deliv-
200 ered to the electric grid and the local DH distribution system (Table 1). The net
201 electric and thermal efficiency in relation to the energy content of the biogas lower
202 heating value (LHV_{biogas} : 9.8 kWh per nm^3) was 0.24 and 0.27, respectively. To-
203 tal net electric and thermal efficiency of the willow in the biogas scenario were
204 4.9 % and 5.5 %, respectively, in relation to the energy content of the feedstock
205 (higher heating value, HHV) entering the biogas process.

206 The digestate was stored in covered tanks at ambient temperature before being
207 spread on annual crops on the dairy farm. The average one-way transportation dis-
208 tance to the field was calculated to 3.7 km using the method in [40] (equation A.1),
209 derived from [41]. A winding factor of 2, a share of arable land of 0.5 and the part
210 of land used for application was assumed to be 0.3.

211 *Modeling of the biogas process.* The biogas process was set up as a mass balance
212 model using data from laboratory-scale experiments on anaerobic co-digestion of
213 willow and liquid manure at the Department of Microbiology, Swedish Univer-
214 sity of Agricultural Sciences (SLU) (unpublished) (Table 2). The composition
215 and volumes of the biogas and digestate were calculated taking into account the
216 biogas yield, CH_4 concentration and elementary composition of the individual
217 feedstock as well as the water removed with the biogas produced. The digestate
218 was assumed to have a density of 1 t per m^3 .

219 The organic loading rate (OLR) of the manure fraction before and after the
220 establishment of the willow was set to 1.5 g of VS per ($\text{dm}^3 \text{ d}$). The first willow
221 harvest of each rotation contributed an additional 1 g of VS per ($\text{dm}^3 \text{ d}$). Subse-

Table 1. Gas engine - combined heat and power unit capacity and performance in the biogas scenario at full production.

Parameter	Value			Unit
Electrical power rating	64			$\text{kW}_{\text{el}}^{\text{engine}}$
Electrical efficiency	0.36			$\eta_{\text{el}}^{\text{engine}}$
Thermal efficiency	0.42			$\eta_{\text{th}}^{\text{engine}}$
<i>Energy input</i>	<i>Codigestion</i>	<i>Manure fraction^b</i>	<i>Willow fraction^c</i>	
biogas	4838	3290	1547	MJ yr^{-1}
<i>Energy output - CHP</i>				
electricity	1742	1184	557	MJ yr^{-1}
heat	2037	1385	652	MJ yr^{-1}
<i>Energy delivered^a</i>				
electricity	1473	1090	383	MJ yr^{-1}
heat	1324	900	424	MJ yr^{-1}

^a Energy delivered to the electric grid and district heating distribution system.

^b The manure fraction was calculated by setting the willow input to 0.

^c The willow fraction was calculated as the difference in output from co-digestion and digesting only the manure fraction.

Table 2. Biogas process, substrate and digestate parameters at full production.

Parameter	Value			Digestate		Unit
	Willow	Manure	Mixture	Total	Willow	
<i>Process specific</i>						
OLR	1.5	1.5	3			g _{VS} dm ⁻³ d ⁻¹
CH ₄ yield	0.103	0.219	0.159			nm ³ kg _{VS} ⁻¹
CH ₄ content	53	65	61			%of biogas
<i>Feedstock specific</i>						
Wet weight	921	6420	7341	7029	798	t per yr
DM	47.7	8.2	13.2	9.9	41.6	%of wet weight
VS/TS	0.98	0.82	0.89	0.85	0.97	g per g
Tot-N	0.5	5.5	3.2	4.5	0.7	%of DM
min-N ^a	0	53	50	68	42	%of Tot-N
Tot-P	0.03	0.62	0.35	0.49	0.04	%of DM
K	0.1	5.1	2.8	3.9	0.1	%of DM
C	37.6	55.5	45.8	46.3	60.2	%of DM

^aThe amount of min-N returned to the field was reduced by 10 % of the min-N content in the digestate to account for ammonia (NH₃) lost during storage and application of digestate [42].

222 quent harvests of willow contributed 1.5 g of VS per (dm³ d). The active digester
223 volume was 869 m³ giving a hydraulic retention time (HRT_{in}) of 39 days when
224 co-digesting at full capacity.

225 Eighteen percent of the C in the willow substrate was converted to gas, yield-
226 ing 83 × 10³ m³ of biogas annually at full capacity.

227 2.2.3. Combustion scenario

228 The willow chips were transported 30 km to the central CHP plant. At the CHP
229 plant, the willow chips were mixed with biomass of forest origin and incinerated
230 in a grate furnace with a steam boiler. The net electric efficiency was set to 28 %
231 and the amount of heat delivered to the DH distribution system was set to 62 % of
232 the energy content of the biomass entering the furnace (HHV).

233 The amount and composition of the bottom ash was based on Swedish CHP
234 plants using similar fuels and technology (wood fuel and grate furnace) [43]. The
235 bottom ash fraction contained 50 % of the feedstock ash content. The energy and
236 emissions from transport of the bottom ash back to the field were included, but
237 field application was excluded since the ash was mixed with digested manure and
238 applied to the field.

239 2.3. Energy balance and emissions from operations

240 Primary energy and emissions from operations were based on the primary
241 energy factors and life cycle emissions of the energy carriers used [44]. An ad-
242 ditional energy input of 20 % and 8 % of the energy content of the diesel used,
243 as well as the emissions related to the production of this energy, were added
244 for the manufacturing and maintenance of tractors and trucks, respectively [45].
245 Emissions and direct energy input for machine operations was determined using
246 operation-specific data (Table B.1).

247 The energy efficiency was calculated as the energy ratio (ER) between the
248 energy delivered and the primary energy input. The HHV of the willow was set to
249 17.64 MJ per t of DM, based on the elementary composition of the feedstock used
250 in the biogas laboratory-scale experiments at the Department of Microbiology,
251 SLU.

252 Dry matter losses during storage were based on a 0.8 % DM reduction for ev-
253 ery month of storage [36], assuming that 25 % of the annual harvest was delivered
254 at the beginning of every three-month period. This resulted in a DM loss of 3.6 %
255 of the total yield. The moisture content (MC) used when calculating transported
256 volumes was 52 %, 31 %, 19 % and 20 % at 0, 3, 6 and 9 months after harvest [36].

257 CH₄ losses from biogas production were set to 2 % of the biogas produced,
258 with 1 % coming from the biogas production phase and 1 % from the digestate
259 storage phase [46, 47].

260 Both systems were assumed to recycle part of the nutrients exported from the
261 field with the harvested willow back to the dairy farm. These nutrients reduced
262 the need for inorganic fertilizers, affecting GHG emissions and the energy balance
263 of each scenario through avoided production. The reduction was calculated based
264 on the primary energy consumption and emissions from the production of mineral
265 fertilizer [48].

266 2.4. Nutrient balances and associated emissions

267 The amount and timing of fertilizer application was taken into account when
268 generating the life cycle inventory (Table B.2).

269 All nutrients present in the feedstock of the biogas scenario were assumed to
270 end up in the digestate. In the direct combustion scenario, all of the N present
271 in the feedstock was assumed to be lost, while 51 % and 45 % of the P and K
272 present in the feedstock was assumed to be returned to the field with the bottom
273 ash [43]. The mineral nitrogen (min-N), total phosphorous (tot-P) and potas-
274 sium (K) content of the digestate and bottom ashes replaced equivalent masses of
275 mineral fertilizer (Table 2).

276 Fertilizer-induced N₂O emissions were calculated applying a conversion fac-
277 tor of 1 % to the applied N. 30 % of the applied N was leached. A conversion
278 factor of 0.75 % was applied to the N in the leached fraction [49]. N₂O emis-
279 sions from above-ground and below-ground organic matter decomposition was
280 included, using the same conversion factors as above. A N content of 2.5 % in the
281 litter and 0.43 % in the stems was assumed [50], with fine roots having the same
282 N content as the stems.

283 2.5. Carbon fluxes in soil and standing biomass

284 The net CO₂ flux between the atmosphere and the biosphere due to the es-
285 tablishment of the willow plantation was calculated as the difference between
286 each scenario and a reference case where no land use change took place. An-
287 nual CO₂ fluxes were modeled as in [16] (equation (C.1) & (C.2)). A modified
288 two-compartment C pool model was used (ICBM) [51, 52] that enabled the use of
289 variable yearly input.

290 The above-ground humification factors (*h* values) and other parameters used
291 in the ICBM model are found in table C.1. The *h* value for below-ground input
292 was multiplied by 2.3 [53].

293 Annual net C flux in the standing biomass was calculated assuming a 45 % C
294 content in willow DM and a 50 % C content in the DM of other crops.

295 In this study, SOC pool changes refer to the entire soil profile, since C allo-
296 cation to different depths varies between crop types. The C input throughout the
297 entire soil profile was calculated as in [16].

298 Land use prior to establishing the willow was assumed to have been green
299 fallow for a period of 20 years, preceded by annual crops long enough to achieve
300 steady state SOC.

301 Annual net C flux due to the digestate was determined as the difference in
302 SOC change between applying co-digestion digestate and applying manure only
303 digestate to the same area of application. The C input and initial SOC values of
304 the green fallow and the digestate application area are found in table B.3.

305 The h value of the digestate (h_{dig}) was calculated as follows: The h values
306 of the manure and willow digestate were estimated ($h_{[m,w]}$) using equation (1),
307 where h_{in} is the h value of the substrate entering the biogas process and $C_{out} \cdot C_{in}^{-1}$
308 represents the C fraction remaining in the digestate for each substrate:

$$h_{[m,w]} = \frac{h_{in}}{C_{out} \cdot C_{in}^{-1}} \quad (1)$$

309 The manure and willow h values (h_m & h_w) were then weighted according to
310 their relative share of C in the digestate ($a_{[m,w]}$) using equation (2).

$$h_{dig} = h_m \cdot a_m + h_w(1 - a_m) \quad (2)$$

311 The resulting h_{dig} was calculated to be 0.48.

312 2.6. Consideration of conversion efficiency

313 Converting biomass to biogas before generating electricity inevitably leads to
314 lower energy efficiency compared with direct combustion in a large-scale CHP.
315 Since the biomass output per hectare of land was identical in both scenarios a
316 strict comparison of the climate impact per energy service becomes biased. One
317 approach used in LCA to overcome this problem is to make the reference flows of
318 both systems equal [8]. This is achieved by including the environmental burdens
319 associated with external processes that fulfill equivalent functions to those lacking
320 in one of the systems studied.

Table 3. Emission values for 1 kWh of electricity delivered to the grid for the Swedish mix in 2008, a fictional mix (Other mix) and heat in a local DH distribution network. Emissions and primary energy values are based on [44].

Electricity source	CO ₂ $\frac{\text{g}}{\text{kWh}}$	CH ₄ $\frac{\text{mg}}{\text{kWh}}$	N ₂ O $\frac{\text{mg}}{\text{kWh}}$	GWP ₁₀₀ $\frac{\text{gCO}_2\text{-eq}}{\text{kWh}}$
Swedish Mix ^a	20	13	1	21
Other Mix ^b	317	565	6	333
Heat Source				
Local DH ^c	62	8	3	63

^a The values for the Swedish mix are approximations based on the composition of the energy production from official statistics, the categorization of which does not necessarily coincide with that of [44].

^b The other mix is composed of 30% nuclear, 30% natural gas generated in a CC-CHP, 30% hard coal generated in a back pressure steam turbine CHP, and 10% wind power. All CHPs are assumed to have a conversion efficiency of 85%. The default power to heat ratio and harmonized efficiency reference values for separate production of electricity and heat of the EU energy efficiency directive were used for allocation of emissions and primary energy calculations [33, 34].

^c The fuel mixture used for the DH plant was made up of 90% biomass, 5% exhaust gas condensation, 4% auxiliary electricity and 1% oil

321 Here, the outputs of heat and electricity were equal in both scenarios in re-
 322 lation to the area used. The lower energy efficiency of the biogas system was
 323 compensated for by adding the emissions and primary energy input from the pro-
 324 duction of other heat and electricity sources (Table 3), making the energy output
 325 of the biogas scenario equal to that of the direct combustion scenario (Fig. 2).

326 Two cases for compensation of energy were modeled. The electricity used
 327 was either the Swedish electricity mix or a fictional mix (here after referred to
 328 as the 'other mix'). The Swedish mix represented electricity with a high share
 329 of renewables, while the energy source in the 'other mix' was 30 % nuclear, 30 %
 330 natural gas, 30 % hard coal and 10 % wind. In both cases the heat used represented
 331 a typical biomass-fired DH system.

332 2.7. Climate impact

333 In order to understand the effect of each system on climate over time, the
 334 time-dependent climate impact [16] was determined for both scenarios, using the
 335 contribution to global mean surface temperature change (ΔT_S) as the indicator.
 336 Since ΔT_S is an instantaneous indicator, only temperature effects realized during

337 the evaluation period are included, making the timing of emissions relative to the
 338 time of evaluation important.

339 In order to investigate how the system affected ΔT_S after the study period (year
 340 53), the temperature change was evaluated until year 100, without making any
 341 assumptions on future land use (after year 53). Hence, it was assumed that no
 342 GHG fluxes affecting ΔT_S took place between the end of the study period and year
 343 100.

344 The contribution to ΔT_S in the n^{th} year of the evaluation period ($\Delta T_S(n)$, equa-
 345 tion 3) was calculated as the sum of all individual temperature response functions
 346 ($\Delta T_S^{CO_2i}$) having their origin in individual emission impulses (E_{x_i}) taking place
 347 prior to year n . E_{x_i} is the emission impulse, E , of gas x emitted in year i of the
 348 study period. The magnitude of the individual temperature response functions was
 349 determined by entering the emission impulses from the time-distributed life cycle
 350 inventory into equation 4, where RE_x is the radiative efficiency of GHG x :

$$\Delta T_S(n) = \sum_{x=1}^3 \sum_{i=1}^n \Delta T_S^{x_i}(t) \quad [\text{K}] \quad (3)$$

$$\begin{cases} \Delta T_S^{CO_2i}(t) = E_{CO_2i} \cdot RE_{CO_2} \cdot \left(k_0 + \sum_{j=1}^5 k_j \exp\left(-\frac{t}{\tau_j^{CO_2}}\right) \right) & [\text{K}] \\ \Delta T_S^{CH_4i}(t) = E_{CH_4i} \cdot RE_{CH_4} \cdot \left(\sum_{i=1}^3 m_j \exp\left(-\frac{t}{\tau_j^{CH_4}}\right) \right) & [\text{K}] \\ \Delta T_S^{N_2O_i}(t) = E_{N_2O_i} \cdot RE_{N_2O} \cdot \left(\sum_{i=1}^3 n_j \exp\left(-\frac{t}{\tau_j^{N_2O}}\right) \right) & [\text{K}] \end{cases} \quad (4)$$

351 Parameters used in equation 4 were the same as in [16].

352 3. Results

353 3.1. Energy efficiency

354 Both the biogas and direct combustion scenarios were net producers of energy,
 355 having an ER of three-fold and 19-fold, respectively.

356 The average amount of energy delivered over the study period was 16 GJ per (ha yr)
357 from the biogas scenario and 141 GJ per (ha yr) from the direct combustion sce-
358 nario. The electricity to heat ratio for the biogas and direct combustion scenarios
359 was 0.91 and 0.45, respectively. As a result, the direct combustion scenario deliv-
360 ered six-fold more electricity and 11-fold more heat than the biogas scenario.

361 The ER between the electricity delivered and primary energy input allocated to
362 electricity was 11 in the direct combustion scenario and 2.3 in the biogas scenario.
363 When the reference flows were forced to be equal by adding heat and electricity
364 to the biogas scenario, the ER dropped to 0.7.

365 3.2. Greenhouse gas fluxes

366 The willow biomass was carbon-neutral over each rotation, as the amount of
367 C emitted when generating energy was the same as that taken up by the willow
368 during its growth. The net CO₂ flux from the biomass to the atmosphere (Ta-
369 ble 4) was positive due to the difference in biomass present before establishing
370 the willow and after the final harvest of the last rotation (Fig. 3a,b).

371 Differences in total GHG emissions between the scenarios were mainly due
372 to SOC stock changes induced by willow C returned with the digestate and CH₄
373 losses in the biogas scenario (Fig. 3a-d).

374 The introduction of willow in the biogas process gave rise to additional diges-
375 tate, increasing the SOC pool of the digestate application area by 11 t of C per ha
376 (325 ha) over 53 years.

377 The average sequestration rate was 432 kg of C per (ha yr) in the willow plan-
378 tation (45 ha) and 236 kg of C per (ha yr) in the digestate application area (325
379 ha). The latter was a larger C sink due to its greater extension compared with the
380 willow plantation (Table 4).

381 CH₄ losses from the anaerobic digestion process and storage of the digestate
382 were large sources of CH₄ emissions in the biogas scenario, explaining almost the
383 entire difference in CH₄ emissions between the two scenarios (Fig. 3c,d).

384 Longer transport distance to the CHP plant gave higher CO₂ emissions from
385 operations in the direct combustion scenario.

386 Biomass and fertilizer-induced emissions were the main sources of N₂O in the
387 system (Fig. 3e,f). Emissions from the manufacturing of mineral fertilizer were
388 slightly lower in the biogas scenario due to a higher recycling rate, leading to more
389 mineral fertilizers being replaced.

Table 4. Total accumulated emissions per hectare for the biogas and direct combustion scenarios over the entire study period, displayed in sources and sinks.

	Biogas			Direct combustion		
	CO ₂ t	CH ₄ kg	N ₂ O kg	CO ₂ t	CH ₄ kg	N ₂ O kg
<i>Sources</i>						
Energy production ^a	180	7	18	25	11	28
CH ₄ leakage ^b		632				
Fertilizer induced N ₂ O ^c			50			50
Biomass induced N ₂ O ^d			70			70
Live biomass - C ^e	4			4		
<i>Sinks</i>						
Soil C - SRC willow	-79			-79		
Soil C - Digestate	-310					
Total	367	639	138	-51	11	148
GWP ₁₀₀ [t (CO ₂ -eq)]	-367	16	41	-51	0	44

^a Energy production includes all machine operations, such as willow production, transport and handling of the residues.

^b CH₄ losses from the digestion process and during storage are included.

^c Fertilizer-induced emissions refer to those attributed to fertilizers applied to the willow.

^d Biomass-induced emissions refer to those attributed to biomass broken down in the field.

^e The live biomass can act as both a sink and a source. Positive emissions are due to the difference in standing biomass prior to the establishment of the willow and after the final harvest of the willow. The willow biomass in itself is carbon-neutral over a complete life cycle.

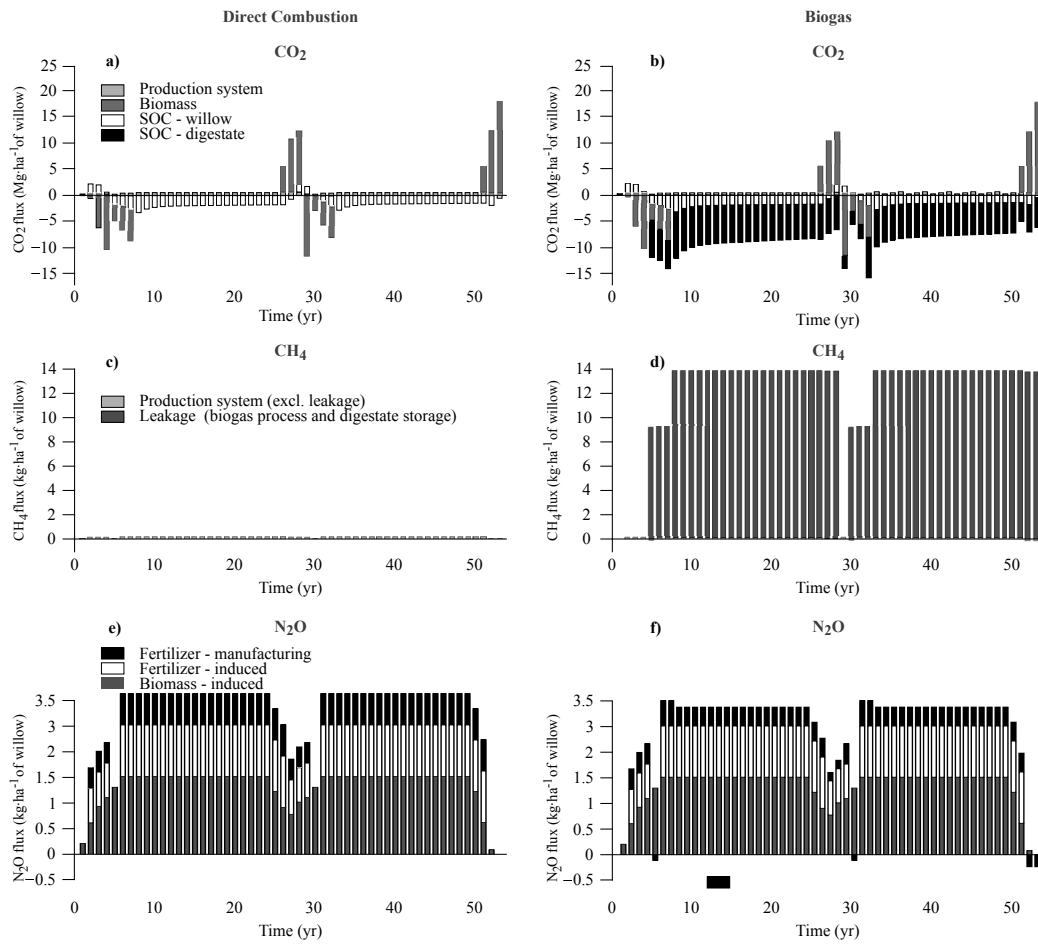


Fig. 3. Time-distributed life cycle inventory of the direct combustion and biogas scenarios. Greenhouse gas (GHG) fluxes from the main sources and sinks of each scenario are shown stacked. Soil organic carbon (SOC) stock changes, CH_4 losses from the biogas process and digestate storage, and reduced mineral fertilizer requirements due to higher recycling rates of nutrients in the biogas system were the principal differences between the two scenarios.

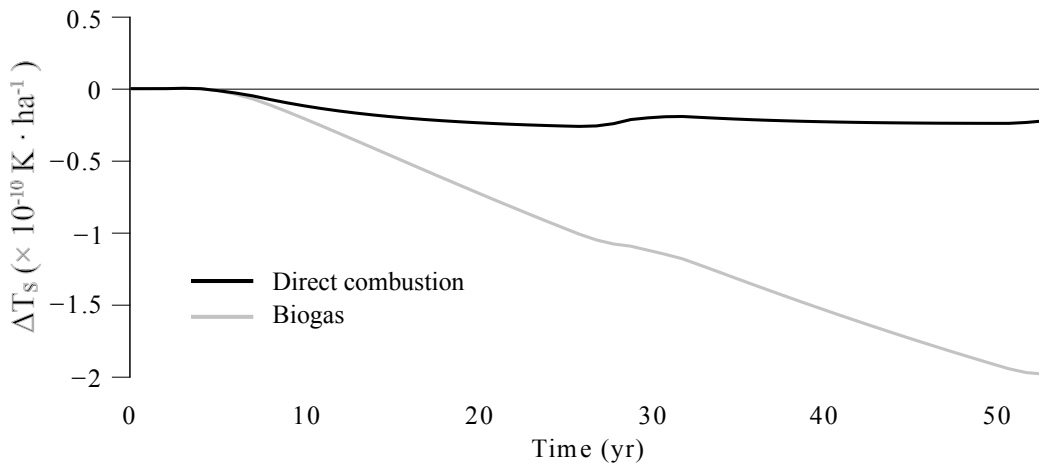


Fig. 4. Contribution to ΔT_S from willow grown for 50 years on 1 hectare of land for heat and power generation using either a biogas engine or direct combustion.

390 3.3. Climate impact

391 Both scenarios made a negative contribution to ΔT_S , counteracting global warm-
 392 ing. The cooling effect per hectare of willow was nine-fold greater in the biogas
 393 scenario than in the direct combustion scenario at the end of the study period
 394 (Biogas: -1.98×10^{-10} K per ha; Direct combustion: -0.22×10^{-10} K per ha in
 395 year 53). Almost all of the decrease in ΔT_S took place during the first rotation of
 396 the direct combustion scenario (Fig. 4). In the biogas scenario ΔT_S continued to
 397 decrease throughout the entire study period, increasing the difference between the
 398 scenarios over time. The main contributing factor to this difference was the SOC
 399 stock changes induced by the C returned to the field with the digestate.

400 The effect of the biogas system on ΔT_S after the reference flows had been
 401 adjusted for its lower energy efficiency depended on the composition of the compen-
 402 sating electricity mix used. When the Swedish mix was used, the cooling
 403 contribution to ΔT_S in the biogas scenario was six-fold that of the direct combus-
 404 tion scenario at the end of the study period (Fig. 5). Using the other mix resulted
 405 in a warming contribution to ΔT_S from the biogas scenario at the end of the study
 406 period.

407 All three scenarios counteracted global warming the first 18 years (Fig. 5).
 408 This effect was due to the rapid and substantial biomass increase changing crop-
 409 ping system (Figs. 3a,b and 6). The cooling effect from the increased C stock in
 410 the biomass dominated the short term trend in ΔT_S , while the SOC stock changes
 411 dominated the long term trend.

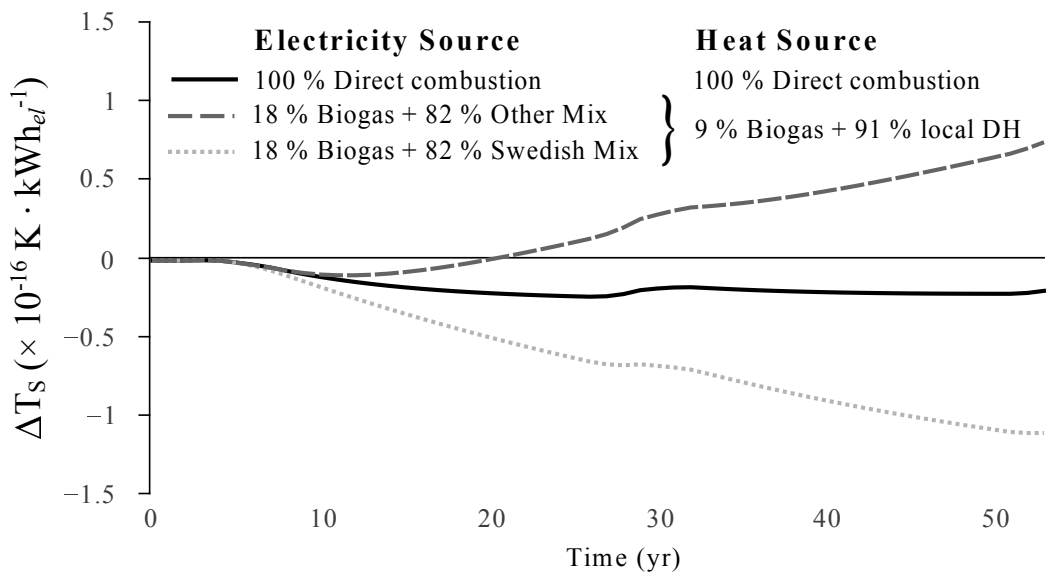


Fig. 5. Contribution to ΔT_S from the electricity of both systems after adjusting the reference flow in the biogas system. The electricity used to compensate for the lower electric output of the biogas scenario was either the Swedish mix or other mix (30 % nuclear, 30 % natural gas, 30 % hard coal and 10 % wind). The heat used to compensate for the lower heat output was assumed to be that of a local DH distribution system, using mainly biomass as the fuel source.

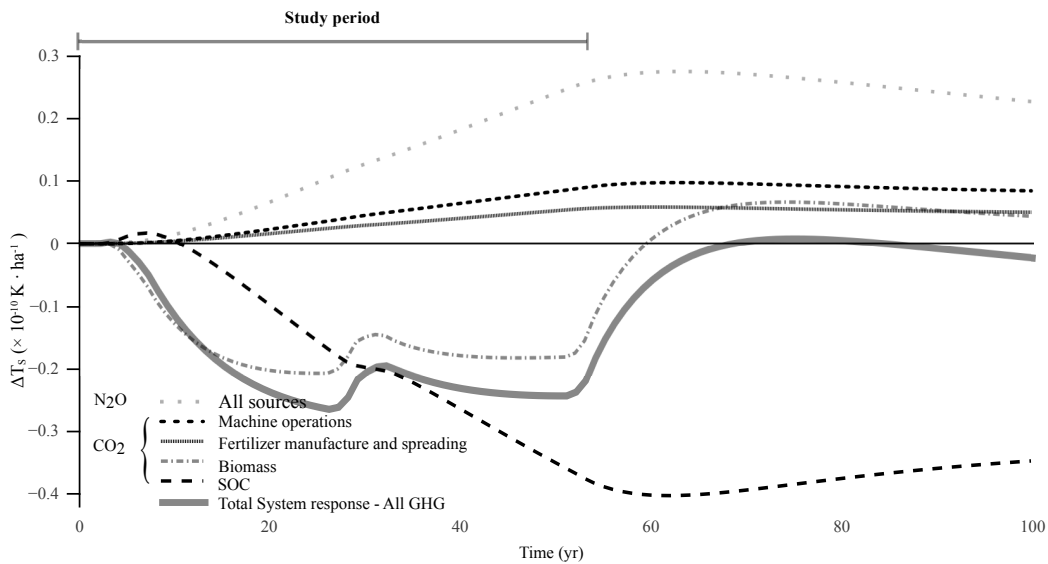


Fig. 6. Effect of emissions produced in year 0 to 53 in the combustion scenario on ΔT_S during and after the study period. The effect on ΔT_S after year 53 is that from GHG emitted in the study period. No assumptions were made on land use after year 53 and no GHG fluxes affecting the temperature response occurred after this year. The thick gray line represents the total system impact.

412 The effect of all activities taking place in the direct combustion scenario during
 413 the study period on ΔT_S after the end of the study period was evaluated. No
 414 assumptions were made on what the land was used for after the final harvest. This
 415 revealed the effect of returning the C in the live biomass to the atmosphere (Fig. 6).
 416 The temperature cooling effect became a warming contribution to ΔT_S within ten
 417 years after the final harvest. This occurred because the relative contribution of the
 418 biomass to the total contribution to ΔT_S was high and the total biomass at the site
 419 after final harvest was lower than before establishing the willow (Table 4). It is
 420 important to consider this effect when evaluating subsequent systems if C stock
 421 changes take place. The total temperature response will be the combined effect of
 422 the not yet realized temperature response from the previous system and the future
 423 temperature response from the new system.

424 3.4. Sensitivity analysis

425 The sensitivity of ER and ΔT_S to changes in some of the input parameters was
 426 tested in a sensitivity analysis. The humification coefficient (h value) of the diges-
 427 tate and the CH_4 yield of the willow fraction were varied since they influenced the
 428 final result of the biogas scenario. The initial SOC level of the willow plantation

Table 5. Primary energy input in the Biogas and Combustion energy production scenarios (MJ/ha/yr).

	Biogas	Combustion
Willow cultivation		
- establishment	349	349
- fertilization ^a	1550	2438
- harvest	3206	3206
- termination	144	144
Transport ^b	98	1355
Handling of residues ^c	233	4
Total	5580	7496

^a Primary energy input into production of fertilizers for the willow plantation was reduced by the amount of primary energy saved through increased recycling of nutrients on the dairy farm.

^b Transport is from field side to the digester or CHP-plant.

^c Handling of residues includes loading, transport to the field and application of recycled digestate and ashes.

429 was also varied since it affected the final results of both scenarios. The parame-
 430 ters were varied in steps of 20 % between 20 % and 200 % of the value in the base
 431 scenarios. The effect on the impact indicator values was calculated and recorded
 432 as % of base scenario.

433 The effect of the CH₄ yield on ΔT_S expressed per kWh of electricity delivered
 434 increased exponentially with a decreasing yield (Fig. 7c), up to the point where
 435 net electric output became negative (which happened at a CH₄ yield of 16 % of
 436 the base scenario) (Fig. 7b,c). This effect is explained by two factors. First, the
 437 recycling rate of C with the digestate increased as CH₄ yield decreased, leading
 438 to a higher sequestration rate of C on the dairy farm. This amplified the climate
 439 impact of the system. Secondly, the energy efficiency of the system decreased with
 440 decreasing CH₄ yield, increasing the sensitivity of the climate impact indicator.

441 The CH₄ yield was the only parameter that affected the ER (Fig. 7b). Apart
 442 from the climate impact per kWh of electricity delivered, the ER was the indicator
 443 most affected by a change in the parameters in the biogas scenario (Fig. 7a,b,d and
 444 e).

445 The *h* value of the digestate and the initial SOC level of the willow planta-
 446 tion affected ΔT_S identically on a per hectare and per kWh basis, since they did
 447 not affect the ER of the biogas scenario, leaving the allocation factor unaltered
 448 (Fig. 7d,e and f).

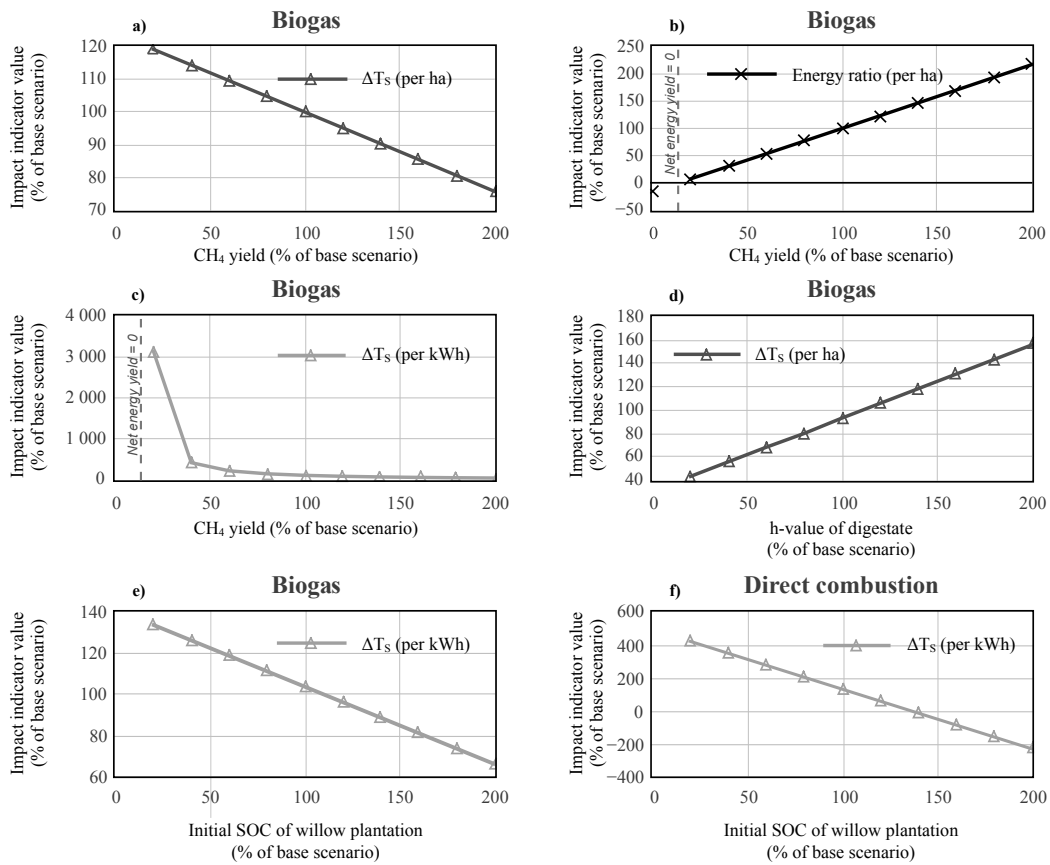


Fig. 7. Sensitivity analysis of the indicators ER and ΔT_s to changes in the CH₄ yield, *h* value of the digestate and initial SOC content in the willow plantation. Parameters that did not affect the energy ratio had an identical impact on the indicators, expressed per hectare and per kWh.

449 ΔT_S was more sensitive to changes in the initial SOC level in the direct com-
450 bustion scenario than in the biogas scenario, since the relative contribution to the
451 climate impact was higher in in the former scenario (Fig. 7e and f).

452 **4. Discussion**

453 Growing SRC willow to generate electricity and heat can be energy-efficient
454 and counteract the current trend in global warming. The direct combustion and
455 biogas scenarios studied were both net energy producers and had a cooling effect
456 on ΔT_S . The cooling effect was stronger in the biogas scenario due to the recy-
457 cling of C with the digestate, resulting in increased SOC stocks. The ratio of the
458 primary energy input to the energy in the biogas produced corresponded to re-
459 sults of other life cycle studies of biogas production from manure, grasses, straw
460 and silage crops [45, 54, 55]. However, the biogas yield from the willow used
461 in this study was very low compared with that from other energy crops used for
462 biogas production. A different pretreatment or added post digestion step would
463 most likely affect the biogas yield and the comparison between the two systems
464 studied.

465 Climate impact from the SOC and biomass stock changes in the biogas sce-
466 nario was several-fold higher and of an opposing sign to the impacts from the
467 fossil inputs and fertilizers used. This came at the cost of net energy output since
468 there was a clear trade-off between maximizing energy efficiency and sequestering C.
469

470 The biogas conversion step enabled a high recycling rate of nutrients and C
471 back to the soil. This higher recycling rate of nutrients may be important for
472 closing the loops in agriculture, but had little impact on the energy efficiency
473 and climate impact in this study. However, the effect of recycling C was very
474 large for both the energy efficiency and climate impact of the system. The bio-
475 gas system was shown to offer a sustained cooling contribution to ΔT_S due to the
476 long term accumulation of SOC. This differentiated it from the direct combustion
477 scenario, which only offered a short-term mitigation effect when it came to coun-
478 teracting global warming. The importance of considering SOC whenever a land
479 use change occur is also evident from the CH_4 losses in the biogas system. This
480 would have had a much larger relative climate impact if the SOC had not been
481 considered.

482 The energy sources used to compensate for the lower ER of the biogas scenario
483 proved to be critical. After adjusting the reference flow of the biogas scenario
484 to be equal to the direct combustion scenario, the external production source of

485 electricity and heat chosen effectively determined whether the biogas scenario had
486 a cooling or a warming influence on ΔT_5 . In all cases the biogas system contributes
487 to lower the climate impact of the electricity mix.

488 If the lower output in the biogas scenario could be compensated for by ex-
489 panding the area of willow cultivation on existing fallow and marginal land which
490 would otherwise not be used for forestry or food production the beneficial climate
491 effects would be very large since more C could be sequestered.

492 If the demand for bioenergy sector products increases, it is possible that the
493 profitability of bioenergy plantations might surpass those of conventional crops on
494 primary farmland. If that is the case, the consequences of indirect land use change
495 (iLUC) have to be taken into account when determining the possible consequences
496 of choosing biogas over direct combustion [56].

497 An important observation from this study was the long-term effects on yield in
498 a scenario where recycling rates are high [57]. The long-term fertilization effect
499 of organic nitrogen and SOC will most likely reduce the need for external inputs
500 per unit of biomass yield in a biogas system. This could lead to increased com-
501 petitiveness of the individual farm, which is an important aspect for the economic
502 sustainability of bioenergy. This has to be viewed in the light of the energy effi-
503 ciency of the system. If the gains from recycled nutrients can not compensate for
504 the lower energy output there is little or no incentive for farmers to choose a less
505 energy-efficient system, no matter what the implications are for the climate. After
506 all, it is the the on-farm profitability of cropping that will ultimately decide the
507 future of bioenergy crops.

508 From an energy security perspective it seems preferable to utilize the feedstock
509 in the most energy efficient way, which in this case was direct combustion. If re-
510 gional development and economy is in the focus of policy makers it makes more
511 sense to support other resources for biogas production which can offer higher
512 yields at lower costs and where technology development needs are smaller. The
513 most obvious advantage of the biogas system was its high mitigation effect against
514 global warming. It is however not obvious that it would be a good policy to sup-
515 port biogas production from willow to mitigate global warming. There might be
516 other systems that may provide the same benefits with higher energy efficiency,
517 for example pyrolysis systems [58]. Unlike the biogas process, the pyrolysis pro-
518 cess stabilises the carbon which further increases its mitigating effects.

519 Another important insight is that SRC willow systems have the potential to
520 produce electricity and heat while counteracting the current trend in global warm-
521 ing at the same time. Whether direct combustion, optimizing the net electrical
522 output, or prior conversion to biogas, optimizing recycling and C sequestration,

523 is preferable is a question of societal priorities. To answer that question, factors
524 other than the energy efficiency and climate impact of the system need to be con-
525 sidered. Some of the issues that need to be taken into account are the economic,
526 social and general environmental aspects of the system, as well as how society
527 uses energy in general.

528 **5. Conclusions**

529 The climate impact and energy efficiency of producing electricity and heat
530 from SRC willow using either a biogas conversion pathway or direct combustion
531 were compared using LCA methodology. Both systems may be net generators of
532 electricity and heat, and may also contribute to counteracting the current trend in
533 global warming due to potential SOC increases, providing an additional benefit
534 to that of replacing non-renewable and fossil fuels in climate change mitigation
535 strategies. An important temporal difference in the climate effect was shown. The
536 cooling influence of the direct combustion system was stabilized after the first
537 rotation of the study period, while the biogas system continued to exert a cooling
538 influence throughout the entire study period. This offers two different options
539 in a policy context, depending on the climate goals considered more important.
540 A clear trade-off between C sequestration and energy efficiency was shown in
541 the biogas scenario, where a decreasing CH₄ yield resulted in a lower energy
542 efficiency, but increased the C recycling, the potential SOC levels and the cooling
543 effect on ΔT_5 per unit of energy produced. If the lower energy efficiency of the
544 biogas system needs to be compensated for using energy from other sources, the
545 climate benefit of the biogas system relative to direct combustion will depend on
546 the external energy source used. In all cases, the SRC willow system contributes
547 to lowering the climate impact of the energy system.

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792 **AppendixA. Transportation distance equation**

$$Td = WF \sqrt{\frac{Ra}{200\pi \cdot n(r) \cdot PU}} \quad (A.1)$$

793 where

794 Td : average transportation distance

795 Ra : area required for spreading of digestate

796 n(r) : share of arable land as a function of the distance to the center.

797 WF : winding factor. Turns straight lind distance into actual road distance.

798 PU : part of land used for application of digestate.

799 **Appendix B. Input data****Table B.1.** Energy and emission data for machine operations over the entire study period.

Moment	primary energy MJ/ha	CO ₂ kg/ha	CH ₄ g/ha	N ₂ O mg/ha
Herbicide application - establishment ^a [59]	273	17	1	25
Plowing ^b [60]	508	32	3	47
Harrowing ^c [60]	624	40	3	58
Seedling production [61]	29040	874	380	13559
Planting [59]	179	11	1	17
Weed control ^d [59]	363	23	2	34
Fertilizer application ^e [60]	714	45	4	67
Harvest ^f [59]	110652	7016	578	10308
Field transport ^g [59]	68894	4368	360	6418
Pre-transport chipping ^h [59]	141035	8942	737	13139
Road transport - scenario 1 ⁱ [36]	9798	621	51	913
Road transport - scenario 2 ^j [36]	153216	10127	588	2687
Herbicide application - termination ^k [59]	136	9	1	13
Rotary cultivator ^l [62]	8902	564	47	829
Shallow soil preparation ^m [62]	3452	219	18	322
Comminution - scenario 1 ⁿ [39]	501914	1451	957	63017
Spreading of digestate, willow only ^o [63, 60, 40]	1275060	80843	6662	118784
Loading and transport of ash ^p [60]	17	1	0	0

^aTrailed sprayer, 3500 l, 24 m.

^b4-furrow reversible plough, autumn. First rotation only.

^cSpring, 70 spikes.

^dWeeder, 12 m.

^eRotina 881.

^fWhole stem harvester, empire 2000.

^g3 tractors, 80kW with dumpers, 12Mg.

^hStationary wood chipper, 400 kW.

ⁱContainertransport with semitrailer, tractor 130kW.

^jSemitrailer, capacity max. 40 Mg, 120 m³.

^kTrailed sprayer, 3500 l, 24 m.

^lShredder, Berti 250 ECF/DT-hedge mower.

^mDisc harrow.

ⁿElectrical stationary comminution.

^oUrine spreader, Star 15 m³ tank with 12 m ramp. Speed 4,1 km/h.

^pVolvo L50 front loader.

Table B.2. Nutrient application scheme in kg per tonne of expected DM in the yield of the SRC willow plantation

Coppicing cycle	Year	N ^a	P	K
First	1 st	0	0.73	2.43
	2 nd	0	0	0
	3 rd	0	0	0
Subsequent	1 st	0	0	0
	2 nd	5	0.73	2.43
	3 rd	0	0	0

^aThe digestate returned to the dairy farm was applied at a fertilizer level of 65 kg of min–N per ha [64]. The resulting area needed for spreading the digestate was 325 ha based on the min–N content of the digestate. The application rate was 21 t of digestate per (ha yr). At this level the P application rate was below the maximum permissible average of 22 kg of P per (ha yr)[65].

Table B.3. Input values used in ICBM for modelling SOC pool changes.

	Green fallow	Annual crops	Digestate application area
Initial SOC level ^a	95.6		107.2
input (above ground) ^b	1.4	3.4	
input (below ground) ^b	2.7	0.7	
input (digestate manure)			0.37
input (digestate willow ₁) ^c			0.41
input (digestate willow ₂) ^c			0.61

^a The initial SOC level refers to the first year of the study period (year 0).

^b Above- and below-ground input for annual crops was used to calculate steady state SOC level 20 years prior to year 0. Above- and below-ground input for green fallow was used to calculate the yearly changes in the green fallow SOC, leading to initial SOC in year 0.

^c The willow fraction of the digestate from the first coppicing cycle was two-thirds of that from subsequent cycles.

800 Appendix C. ICBM Equations and parameters

801 Appendix C.1. ICBM Equations

$$Y_{[a,b]}(t) = (Y_{[a,b]}_{t-1} + i_{[a,b]}_{t-1}) \cdot \exp^{-k_y r_e} \quad (\text{C.1})$$

$$O(t) = (O_{t-1} - (f(Y, i) + g(Y, i))) \cdot \exp^{-k_o r_e} + (f(Y, i) + g(Y, i)) \cdot \exp^{-k_y r_e} \quad (\text{C.2})$$

where

$$f(Y, i) = \frac{h_a \cdot k_y}{k_o - k_y} \cdot (Y_{a_{t-1}} + i_{a_{t-1}})$$
$$g(Y, i) = \frac{h_b \cdot k_y}{k_o - k_y} \cdot (Y_{b_{t-1}} + i_{b_{t-1}})$$

802 *AppendixC.2. Parameter and variable descriptions*

803 *Y* : Young soil organic carbon pool

804 suffix *a* : refers to the above ground fraction of the young pool

805 suffix *b* : refers to the below ground fraction of the young pool

806 *O* : Old soil organic carbon pool

807 *h* : Humification coefficient. Determines how much of the C broken down in a
808 time step that ends up in the old pool and how much is returned to the atmosphere
809 as CO₂

810 *k_Y* : Decay constant of young pool.

811 *k_O* : Decay constant of old pool.

812 *r_e* : Decomposer activity factor. Affects rate of decomposition. Depends on
813 external factors such as soil temperature and moisture content.

814 For further explanation of ICBM see [51, 66, 16]

815 *AppendixC.3. Parameter values*

Table C.1. Parameters used in ICBM for modelling SOC pool changes.

Parameter	Value
k_Y	0.8
k_O	0.009
$h_{\text{annual crops \& fallow}}$	0.15
$h_{\text{willow residues}}$	0.15
$h_{\text{in: willow wood}}$	0.34
$h_{\text{in: manure}}$	0.35