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Energy analysis of willow production for bioenergy in Sweden

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ABSTRACT

Energy from biomass, including lignocellulosic crops such as willow (*Salix* spp.), is expected to increase in importance in Sweden. This study assesses the average annual net energy yield and the ratio between gross energy yield and total primary energy input for well-managed current commercial willow production systems in Sweden subject to three levels of fertilization with mineral nitrogen (N): N-high, N-medium, and N-zero. The average annual net energy yields are estimated at 175, 133, and 86 GJ ha^{-1} yr^{-1}, and the (dimensionless) energy ratios are estimated at 19, 32, and 47, for N-high, N-medium, and N-zero, respectively. Thus, there is a trade-off between achieving a high net energy yield and achieving a high energy ratio. Since the total primary energy input amounts to ≤ 5% of the gross energy yield in all cases, and the amount of arable land is limited, productivity increases may be considered more important than energy efficiency improvements. Substantial improvements in energy performance can be achieved by increasing harvest levels and improving energy efficiency in ammonia production and biomass transportation. The results should be interpreted with caution since several input parameters, especially energy use in ammonia production, fuel consumption rates, and the yield response to fertilization, are associated with considerable uncertainties.

1. Introduction

The Swedish government has decided that Sweden should be one of the world's first fossil-free welfare nations. By 2045, no net greenhouse gas (GHG) emissions are to be emitted to the atmosphere [1], and, by 2030, the vehicle fleet is supposed to be independent of fossil fuels [2]. Bioenergy is considered critical in reaching these goals [3,4]. Currently supplying ca. 23% of the total primary energy demand [5], bioenergy is already an important part of the Swedish energy mix. Perennial lignocellulosic crops, such as willow (*Salix* spp.), are considered attractive options since their production requires less energy [6], and has less of a negative environmental impact [7–9], than production of annual crops such as sugar beets, rapeseed, and wheat.

Willow species are characterized by fast growth, large biomass production potential, limited pest problems, high genetic diversity, short breeding cycles, and high resprouting capacity, i.e., ability to produce new shoots from the same stump after harvest [10]. Willow has been grown commercially for bioenergy in Sweden since the 1990s, primarily in the southern and central parts of the country. While the cultivated area is small, ca. 10,000 ha [11], Sweden is at the forefront of commercial willow plantations for bioenergy [12]. Plantations are typically managed as short-rotation coppice, i.e., multiple harvests and regrowth from the same stump [7]. So far, willow production has provided solid fuels for heat and power generation but may in the future also provide feedstock for production of liquid and gaseous fuels meeting stringent limits on GHG emissions [13].

Previous studies on willow production for bioenergy in Sweden have analyzed the introduction and development of commercial willow plantations [14], identified the reasons for slower-than-expected expansion and lower-than-expected yields [15], developed yield models for commercial willow plantations [16], estimated yields in experimental and commercial plantations and assessed impacts on groundwater and soil organic carbon [11], quantified divergences in yield levels between experimental and commercial plantations [17], evaluated cost reduction possibilities [18], assessed climate impacts [19], and studied how weeds are best controlled [20] and how different rates of mineral nitrogen (N) fertilization affect yields [21]. Studies have also evaluated systems that provide additional functions besides biomass supply [22], e.g., phytoextraction of cadmium and other contaminants on arable land [23] and treatment of sludge and nutrient-rich

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wastewaters [24,25].

Several energy analyses of Swedish willow production systems for bioenergy have also been made [6,26–29]. However, whereas fertilization is an important management aspect that strongly influences yield [12,16,21] as well as energy performance, only one study, namely González-García et al. [28], has previously investigated how different levels of N fertilization affect the performance of Swedish willow production systems. González-García et al. [28] found that willow production without the use of mineral N was more energy efficient (i.e., had a higher energy output: input ratio) than fertilized willow production. However, despite the use of yield data from a large set of Swedish commercial plantations, lack of data about fertilization levels prevented a solid analysis of the relationship between N fertilization and yield levels. It was assumed that plantations with high yields were fertilized with N, while plantations with low yields were not fertilized [28]. However, many factors influence yields, and a high level of fertilization does not guarantee a high yield, if, e.g., soil quality is poor, weather conditions are unfavorable, or the plantation is infested with pests. Further, the energy analysis was only a minor part of the study.

Thorough studies of the effects of different levels of N fertilization on the performance of Swedish willow production systems are therefore lacking. This paper aims to fill this knowledge gap by providing a detailed and up-to-date energy analysis of willow production for bioenergy in Sweden. The average annual net energy yield (*net energy yield*, for short), and the ratio between the gross energy yield and the total primary energy input (*energy ratio*, for short), are estimated for well-managed current commercial Swedish willow production systems subject to three levels of fertilization with mineral N. The study also aims at contributing to the debate about sustainable bioenergy production systems.

2. Materials and methods

The method consists of four steps: 1) definition of the willow production systems (Section 2.1); 2) inventory analysis of management operations and material inputs in the studied production systems (Section 2.2); 3) energy analysis (Sections 2.3); and 4) assessment of performance (Section 2.4). The assessment is based on a detailed and thorough review of management operations and energy use. Predominantly empirical data, collected from a wide range of published sources as well as experts, are used in the assessment.

2.1. Willow production systems and system boundaries

Willow production with three different levels of fertilization with mineral N are studied (Table 1): no N fertilization (N-zero), a medium level of N fertilization (N-medium), and a high level of N fertilization (N-high). Detailed information about fertilization practices in Swedish willow plantations is not available. Therefore, it is not known how these fertilization levels compare to current actual practice. The different levels are, however, all considered realistic and practically feasible. The medium level, with 160 kg ha^{-1} of mineral N applied per cutting cycle, is fairly close to the most recent fertilization recommendation for willow production in Sweden: 220 kg ha^{-1} of mineral N applied per cutting cycle [21].

Table 1
Definitions of the production systems studied here.

Case	Definition
N-high	High level of N fertilization: 480 kg ha^{-1} of mineral nitrogen (N) applied in each cutting cycle: 160 kg N ha^{-1} yr^{-1} for 3 years after each harvest (except the last), corresponding to, on average, 140 kg N ha^{-1} yr^{-1} over the plantation life cycle.
N-medium	Medium level of N fertilization: 160 kg ha^{-1} of mineral N applied in the first year after each harvest (except the last), corresponding to, on average, 40 kg N ha^{-1} yr^{-1} over the plantation life cycle.
N-zero	No N fertilization (0 kg N ha^{-1} yr^{-1}).

Other than the level of fertilization, the three cases are subject to the same management operations (but the number of harvests differ, see Section 2.2.1). Production in southern/central Sweden is considered, but the analysis is not specific to any particular site or type of soil. The production systems are managed as short-rotation coppice according to available management recommendations and considered representative of current and commercial plantations.

The system boundaries include the primary production of energy carriers and material inputs, field management operations and transportation of wood chips to the bioenergy-conversion site (heat plant or combined heat-and-power plant), see Fig. 1. The energy embodied in agricultural machines and implements (plows, harrows, etc.) is also included. The energy use is fully allocated to the studied production systems. Human labor, infrastructure for transportation, and biomass conversion to secondary energy carriers (heat/electricity) are not included.

2.2. Inventory of management operations

The management operations and material inputs of the production systems were determined based on information from practitioners and managers of willow plantations, information from the literature, and assumptions based on our own experience, see Table 2, which also specifies the time (year) of performance.

Willow cultivation is assumed to be well established, implying that specialized machinery is available and employed to a large extent on a yearly basis. The choice of machinery and management operations is based on a number of assumptions: 1) willow plantations are established on existing cropland previously cultivated with annual crops; 2) plantations are established on private commercial farms that have access to their own or hired machinery; 3) the soil has an average production potential; 4) management operations are not hindered by any physical conditions of the fields, such as size, shape, and drainage; 5) good agricultural practice, regarding, e.g., soil preparation, planting, and weed control, is applied at all stages; 6) no irrigation is applied; and 7) all plantations are terminated after 24 years. More information about the management operations is available in the Supplementary material, Section S1.

2.2.1. Data on fertilization and yields

Data on yields, and on the relationship between yield and level of N fertilization, were obtained from fertilization trials by Aronsson et al. [21]. The trials were conducted between 2008 and 2010 at five sites with commercial willow plantations in central Sweden (Högsta, Åsby, Lindberg, Djurby, and Hjulsta), using modern willow varieties in a randomized block design with four replicates. Mineral N was applied at four different rates: 1) no fertilization ("Control"); 2) 160 kg N ha^{-1} in a single dose after harvest ("Economy"); 3) 60, 100, and 60 kg N ha^{-1} in the first, second, and third year after harvest, respectively ("Normal"), and 4) 160 kg N ha^{-1} in the first, second, and third year after harvest ("Intensive"). The fertilization levels for N-high, N-medium, and N-zero correspond to the "Intensive," "Economy," and "Control" treatments in Aronsson et al. [21], respectively.

Yields from Aronsson et al. [21] represent estimates of the average standing crop biomass in the five sites after three years, calculated using data from annual field measurements of shoot diameters and site-specific allometric equations describing the relationship between shoot diameter and dry mass. To better represent the plantations considered here, the yield data from Aronsson et al. [21] were adjusted by applying a correction factor of 0.9 in order to account for losses associated with harvest (Table 3). Further, the lengths of the cutting cycles were adjusted, and the yields were adjusted accordingly. Yield levels were assumed to be the same for all harvests, except for the first and the last. The yield of the first harvest was assumed to be 37.5% lower than that

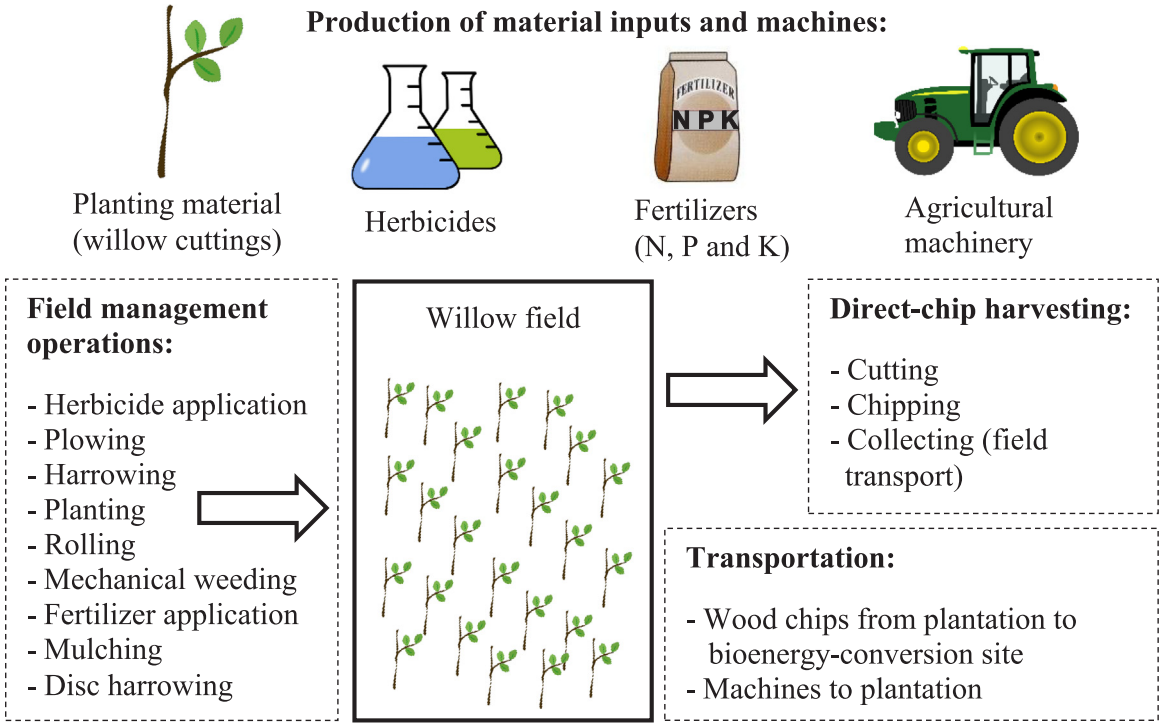


Fig. 1. System boundaries and processes of the studied willow production systems. Table 2 specifies which operations are performed in each case. A detailed description of the management operations is given in the Supporting information, Section S1.

of the second (in all cases), based on Mola-Yudego and Aronsson [16]. The yield in the last harvest was calculated assuming constant but 37.5% lower growth rate than between previous harvests (Table 3).

Aronsson et al. [21] measured yields after three years. We considered that the plantations fertilized with 0 and 160 kg N ha^{-1} (corresponding to the N-zero and N-medium case, respectively), yielding 17.6 and 28.0 Mg dry matter (DM) ha^{-1} after three years (see Table 3), would not likely be harvested at that time in practice, since farmers strive for cost-efficient management. According to Henriksson Salix AB, the largest commercial actor on willow cultivation in Sweden, the optimal harvest time is when stems that measure 6 cm in diameter 30 cm above ground can easily be found. This corresponds to ca. 30 Mg DM ha^{-1} [30]. In order to model more realistic and cost-efficient management, the lengths of the cutting cycles in the N-zero and N-medium cases were set to five and four years, respectively, and the yields were adjusted accordingly, assuming a constant growth rate. For example, given that the growth rate is 5.9 Mg DM ha^{-1} yr^{-1} in the N-zero case, after five years, the standing crop biomass is 29.4 Mg DM ha^{-1} (before deducting losses associated with harvest), which is closer to the optimal harvest point.

The test sites in the trials by Aronsson et al. [21] differ in many ways: two different clones (Tora and Jorr), planted between 1995 and 2005 on clay and silty clay soils, were used, and the cutting cycles in which the trials were performed ranged between second and fifth for the different plantations. Yield variations (6.5–24 Mg DM ha^{-1}) in the control treatment (no fertilization) reflect differences in soil quality among the sites. Plantations in all five test sites responded to fertilization, but the response varied considerably among sites. This variation was evened out somewhat by using the average yield response from all five test sites. Nevertheless, the yield response to fertilization is an uncertain parameter.

The level of fertilization is one of the most important factors influencing the yield [12,16,21], but many other factors are also known to matter, e.g., soil quality, climate, weather, cutting cycle, age of plantation, experience and engagement among farmers, policies (e.g., the size of subsidies), weeding, pests and diseases, animal browse, and choice of clones [15,31]. In addition to other climate conditions, precipitation during the growing season is a particularly critical parameter [32]. We stress that the fertilization rates and yield levels used here were chosen to represent current and well-managed commercial Swedish willow production systems.

The most recent synthesis of the available knowledge concerning willow yields in Sweden (based on data from 16 publications encompassing 466 plot measurements and 1640 commercial plantations) shows that experimental plots on average yield 7.7 Mg DM ha^{-1} yr^{-1}, while commercial plantations have lower yields – on average 2.6, 4.2, and 4.5 Mg DM ha^{-1} yr^{-1} in the first, second, and third harvest, respectively [11]. The yield levels used here are thus in line with yield levels in Swedish experimental plantations, and similar to the best performing commercial plantations [12].

The fertilization rates used here are all considered realistic and feasible. However, the optimal fertilization level in a given situation is influenced by several (partly interacting) factors, not the least the prices on biomass and mineral fertilizers, see, e.g., Aronsson and Rosenqvist [33]. Based on the results from the field trials and on economic considerations, Aronsson et al. [21] recommended that modern bred willow varieties grown on reasonably suitable sites be fertilized with 60, 100, and 60 kg N ha^{-1} the first, second, and third year after harvest, respectively, starting in the second cutting cycle.

2.3. Energy analysis

Direct energy inputs consist of diesel and oil used in agricultural machines (solar energy incorporated in the biomass through photosynthesis is not considered). Indirect energy inputs consist of all forms of energy used to extract, refine, process, transport, and/or produce energy or materials that are used in the studied production systems, e.g., energy used to produce fertilizers and tractors. The indirect energy inputs associated with a product or material are also referred to as *embodied* or *virtual energy*, and typically reported in MJ kg^{-1}, i.e., the energy needed to produce 1 kg of the material or product.

Mikkola and Ahokas [34] reviewed the data available to assess

Table 2
Management operations, time of performance, and machines used in the studied willow production systems. N-high, N-medium, and N-zero refer to willow grown with high and medium levels of N fertilization and without N fertilization, respectively. Only field operations are listed in this table. Off-field activities, such as transport, are not listed but are included in the energy analysis. More information about the management operations is available in the Supplementary material, Section S1. N/A = not applicable.

Management operation		Time of operation (year)			Machine	Implement
		N-high	N-medium	N-zero		
Field preparation	Herbicide application	−1	−1	−1	Tractor, 90 kW	Boom sprayer
	Plowing	−1	−1	−1	Tractor, 160 kW	Plow
Establishment phase	Harrowing	0	0	0	Tractor, 160 kW	Cultivator
	Planting	0	0	0	Tractor, 90 kW	Planter
	Rolling	0	0	0	Tractor, 160 kW	Roller
	Herbicide application	0	0	0	Tractor, 90 kW	Boom sprayer
	Mechanical weeding	0	0	0	Tractor, 90 kW	Row cultivator
	Mechanical weeding	0	0	0	Tractor, 90 kW	Row cultivator
First cutting cycle	Fertilizer application (N)	1	1	N/A	Tractor, 90 kW	Normal fertilizer spreader
	Fertilizer application (N)	2	N/A	N/A	Tractor, 90 kW	Normal fertilizer spreader
	Fertilizer application (N)	3	N/A	N/A	Tractor, 90 kW	High fertilizer spreader[a]
	Harvest (cutting)	4	4	4	Self-propelled forage harvester	Harvester head
	Harvest (collecting)	4	4	4	Tractor, 90 kW	Trailer field transport
Second cutting cycle	Fertilizer application (N)	5	5	N/A	Tractor, 90 kW	Normal fertilizer spreader
	Fertilizer application (N)	6	N/A	N/A	Tractor, 90 kW	High fertilizer spreader[a]
	Fertilizer application (N)	7	N/A	N/A	Tractor, 90 kW	High fertilizer spreader[a]
	Harvest (cutting)	7	8	9	Self-propelled forage harvester	Harvester head
	Harvest (collecting)	7	8	9	Tractor, 90 kW	Trailer field transport
Third cutting cycle	Fertilizer application (N)	8	9	N/A	Tractor, 90 kW	Normal fertilizer spreader
	Fertilizer application (N)	9	N/A	N/A	Tractor, 90 kW	High fertilizer spreader[a]
	Fertilizer application (N)	10	N/A	N/A	Tractor, 90 kW	High fertilizer spreader[a]
	Harvest (cutting)	10	12	14	Self-propelled forage harvester	Harvester head
	Harvest (collecting)	10	12	14	Tractor, 90 kW	Trailer field transport
Fourth cutting cycle	Fertilizer application (N)	11	13	N/A	Tractor, 90 kW	Normal fertilizer spreader
	Fertilizer application (N)	12	N/A	N/A	Tractor, 90 kW	High fertilizer spreader[a]
	Fertilizer application (N)	13	N/A	N/A	Tractor, 90 kW	High fertilizer spreader[a]
	Harvest (cutting)	13	16	19	Self-propelled forage harvester	Harvester head
	Harvest (collecting)	13	16	19	Tractor, 90 kW	Trailer field transport
Fifth cutting cycle	Fertilizer application (N)	14	17	N/A	Tractor, 90 kW	Normal fertilizer spreader
	Fertilizer application (N)	15	N/A	N/A	Tractor, 90 kW	High fertilizer spreader[a]
	Fertilizer application (N)	16	N/A	N/A	Tractor, 90 kW	High fertilizer spreader[a]
	Harvest (cutting)	16	20	24	Self-propelled forage harvester	Harvester head
	Harvest (collecting)	16	20	24	Tractor, 90 kW	Trailer field transport
Sixth cutting cycle	Fertilizer application (N)	17	21	N/A	Tractor, 90 kW	Normal fertilizer spreader
	Fertilizer application (N)	18	N/A	N/A	Tractor, 90 kW	High fertilizer spreader[a]
	Fertilizer application (N)	19	N/A	N/A	Tractor, 90 kW	High fertilizer spreader[a]
	Harvest (cutting)	19	24	N/A	Self-propelled forage harvester	Harvester head
	Harvest (collecting)	19	24	N/A	Tractor, 90 kW	Trailer field transport
Seventh cutting cycle	Fertilizer application (N)	20	N/A	N/A	Tractor, 90 kW	Normal fertilizer spreader
	Fertilizer application (N)	21	N/A	N/A	Tractor, 90 kW	High fertilizer spreader[a]
	Fertilizer application (N)	22	N/A	N/A	Tractor, 90 kW	High fertilizer spreader[a]
	Harvest (cutting)	24	N/A	N/A	Self-propelled forage harvester	Harvester head
	Harvest (collecting)	24	N/A	N/A	Tractor, 90 kW	Trailer field transport
Field termination & restoration	Herbicide application	24	24	24	Tractor, 90 kW	Boom sprayer
	Mulching	24	24	24	Tractor, 160 kW	Mulcher
	Disc harrowing	24	24	24	Tractor, 160 kW	Disc harrow
	Disc harrowing	24	24	24	Tractor, 160 kW	Disc harrow
	Herbicide application	24	24	24	Tractor, 90 kW	Boom sprayer
	Fertilizer application (P, K)[a]	24	24	24	Tractor, 90 kW	Normal fertilizer spreader

[a] In reality, fertilizers are seldom applied up until the third year after harvest, since few farmers have access to the required special machine, i.e., the high fertilizer spreader. Also, mineral phosphorus (P) and potassium (K) are seldom applied in commercial Swedish willow plantations. These operations are, however, considered good practice and therefore included.

indirect energy inputs associated with agricultural machinery in bioenergy production and concluded that such data are generally old, of questionable quality, or lacking. There is no comprehensive review or database of energy inputs in the manufacture of agricultural machinery; these inputs are often estimated using data from the automobile or steel industry, although it is not known how well these data represent modern agricultural machines that contain a large share of materials other than steel, e.g., plastic, rubber, fiberglass, and high-tech technology. The energy embodied in machines and implements were thus calculated using data associated with large uncertainties.

The energy analysis gives a complete overview of the energy inputs and outputs during a specified reference period. Here, two reference periods are used: 1 year and 24 years, the latter being the plantation lifespan. Energy flows are expressed as gigajoule (GJ) ha^{-1} yr^{-1} or as GJ ha^{-1} over the lifespan of the plantation. All energy inputs are aggregated (i.e., there is no differentiation among different types of energy sources), and expressed as primary energy. Higher heating values are used based on Bossel [35] and Frischknecht et al. [36]. In a few cases, we use data from sources that have not specified the kind of heating values (higher or lower). Information about the difference between lower and higher heating values, and the reasons for choosing the latter, is available in the Supplementary material, Section S2. A detailed description of the assessment of energy inputs, and the data used, is given in the Supplementary material, Section S3.

Table 3
Willow production system yields. N-high, N-medium, and N-zero refer to willow grown with high and medium levels of N fertilization and without N fertilization, respectively. DM = dry matter.

Parameter	Unit	N-high	N-medium	N-zero
Original data from fertilization trials by Aronsson et al. [21]: average values from all five test sites				
Harvest yield level after three years	Mg DM ha^{-1}	39.5	28.0	17.6
Average annual growth rate	Mg DM ha^{-1} yr^{-1}	13.2	9.3	5.9
Data used here				
Length of cutting cycle	Year	3[a]	4	5
Total number of harvests		7	6	5
Yield level per harvest[b]	Mg DM ha^{-1}	35.5	33.6	26.5
Yield level in the first harvest[c]	Mg DM ha^{-1}	22.2	21.0	16.5
Yield level in the last harvest[d]	Mg DM ha^{-1}	37.0	21.0	16.5
Total yield (all harvests), dry basis	Mg DM ha^{-1}	237	176	112
Total yield (all harvests), fresh basis[e]	Mg fresh biomass ha^{-1}	460	343	218
Average annual yield level	Mg DM ha^{-1} yr^{-1}	9.9	7.4	4.7

[a] The length of cutting cycle is three years for all cutting cycles except the seventh and final, which is five years, in order to make the lifespan of all cases equal in length (24 years).

[b] Yield level per harvest, used for all harvests except the first and last, is calculated as the product of the average annual growth rate (assuming constant growth rate), the length of the cutting cycle, and a correction factor of 0.9 to account for harvest-associated losses.

[c] In the first harvest, the yield level was assumed to be 37.5% lower than in the second (in all cases), based on Mola-Yudego and Aronsson [16], according to which yields are 60% higher after the first harvest, since the stools have then developed a better root system that takes up water and nutrients more efficiently.

[d] In the final harvest, the yield level is calculated assuming a constant growth rate, but one that is 37.5% lower than between previous harvests, based on Mola-Yudego and Aronsson [16].

[e] Calculated based on a moisture content at the time of harvest of 48.5%, representing the average value of > 200 measurements of moisture content in willow chips harvested between October 2015 and May 2016 in southern Sweden (unpublished data measured by Henriksson Salix AB).

Table 4
Energy performance of the studied willow systems. N-high, N-medium, and N-zero refer to willow grown with high and medium levels of N fertilization and without N fertilization, respectively. Numbers may not add up due to rounding.

Performance indicator	Unit	N-high	N-medium	N-zero
Total primary energy input over the plantation life cycle[a]	GJ ha^{-1}	228	104	45
Gross energy yield over the plantation life cycle[b]	GJ ha^{-1}	4440	3300	2110
Net energy yield over the plantation life cycle[c]	GJ ha^{-1}	4210	3200	2060
Average annual net energy yield[d]	GJ ha^{-1} yr^{-1}	175	133	86
Energy ratio[e]	dimensionless	19	32	47
Total primary energy input relative to gross energy yield	% of gross energy yield	5.1	3.1	2.1

[a] The sum of direct and indirect energy inputs including energy required to produce material inputs and energy embodied in machines and implements.

[b] The energy contained in the harvested biomass, calculated as the product of the harvest yields from Table 3 and the energy content of harvested willow biomass, see Section 2.3.

[c] Calculated as the gross energy yield (the energy contained in the harvested biomass) minus the total primary energy input.

[d] Calculated as the net energy yield divided by the plantation lifespan (24 years in all cases).

[e] Calculated as the ratio between the gross energy yield and the total primary energy input.

The energy outputs, i.e., the gross energy yields of the studied production systems, were calculated as the product of the biomass yields (Table 3) and the energy content of the harvested biomass. The energy content of willow biomass was taken from Börjesson [6] and refers to the higher heating value of harvested willow biomass from established plantations in the second or a subsequent cutting cycle (18.7 MJ kg^{-1} of DM biomass).

2.4. Energy performance indicators

Two main indicators are used to measure the performance of the studied willow production systems: the average annual net energy yield (*net energy yield*, for short), and the energy ratio. The net energy yield is calculated as the gross energy yield (the energy contained in the harvested biomass) minus the total primary energy input, divided by the plantation lifespan (24 years). The net energy yield indicates the average annual productivity of the systems. The energy ratio is calculated as the ratio between the gross energy yield and the total primary energy input and indicates the energy efficiency of the production system.

2.5. Sensitivity analysis

Several of the parameters are associated with considerable uncertainties and/or natural variability. The influence on the results of a selection of parameters considered highly uncertain – energy use in ammonia production, energy embodied in machines and implements, and fuel consumption – was investigated using sensitivity analysis, i.e., by varying parameter values one at a time. A detailed description of the sensitivity analysis is given in the Supplementary material, Sections S4.1–S4.3, where parameter ranges are also presented.

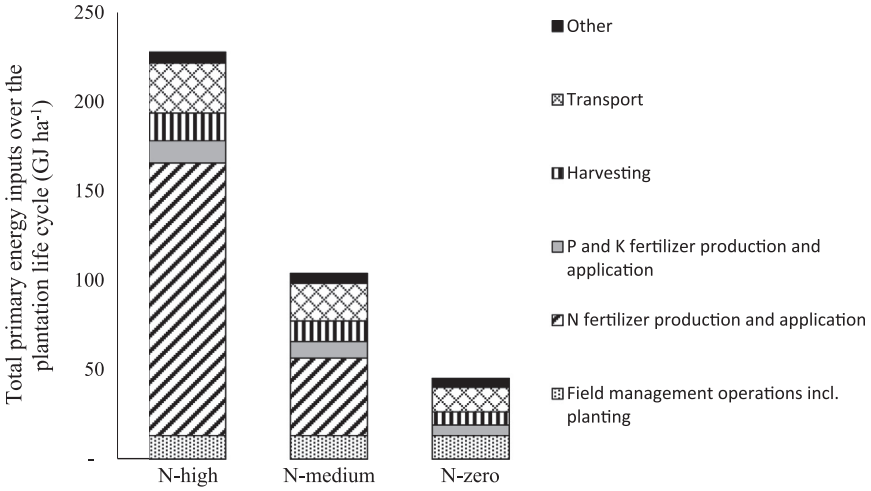


Fig. 2. Total primary energy inputs over the plantation life cycle and the contribution from management operations and/or material inputs. The category "Other" includes production and application of herbicides and energy embodied in machines and implements. A detailed breakdown with more categories is available in the Supporting information, Section S5.

3. Results

3.1. Energy ratios and net energy yields

Table 4 presents the results of the energy analysis. The average annual net energy yields are estimated at 175, 133, and 86 GJ ha^{-1} yr^{-1}, and the energy ratios are estimated at 19, 32, and 47, for N-high, N-medium, and N-zero, respectively. That is, for every unit of primary energy input, the willow systems yield between 19 and 47 units of primary energy in the form of biomass. Higher net energy yields and energy ratios correspond to better performance from an energy point of view. N-high has the highest net energy yield but the lowest energy ratio, while N-zero has the highest energy ratio but the lowest net energy yield. In other words, N-high, corresponding to intensive production, is the most productive but least energy efficient production system, while N-zero, corresponding to extensive production, is the least productive but most energy efficient production system. N-medium is in between the N-zero and N-high cases in terms of both net energy yield and energy ratio. The energy ratios are sensitive to changes in the total primary energy input, which is small in comparison to the gross energy yield. The total primary energy inputs correspond to ca. 2%, 3%, and 5% of the gross energy yields for N-zero, N-medium, and N-high, respectively (Table 4).

N fertilization (production and application) dominates the total primary energy input for N-high (67%) and N-medium (42%), see Fig. 2, with production accounting for 99% of the total energy inputs associated with N fertilization in both cases. The second-largest primary energy input for N-high and N-medium, and the largest for N-zero, is transport. In all cases, the transport of wood chips to the bioenergy-conversion site dominates the energy input associated with transport, followed by the return of the empty wood-chip truck from the bioenergy-conversion site to the willow plantation and the transport of machines to the plantation. While the studied production systems depend on the use of several machines and implements, their embodied energy contributes < 4% of the total primary energy input in all cases (Table 7).

The energy inputs associated with field management operations (plowing, harrowing, rolling, mechanical weeding, planting, mulching, and disc harrowing) and with the production of the planting material are the same in all three cases (Fig. 2). The energy inputs associated with P and K fertilizer production and application, and with harvesting and transport, are proportional to willow yields, hence do not vary when expressed per unit of biomass yield (Table 5).

Table 5
Primary energy input per unit of biomass yield (GJ Mg^{-1} DM). N-high, N-medium, and N-zero refer to willow grown with high and medium levels of N fertilization and without N fertilization, respectively.

Management operations and/or material inputs	N-high	N-medium	N-zero
Field management operations including planting	0.06	0.07	0.12
N fertilizer production and application	0.64	0.25	0.00
P and K fertilizer production and application	0.05	0.05	0.05
Harvesting	0.07	0.07	0.07
Transport	0.12	0.12	0.12
Other	0.03	0.03	0.04
Total	0.96	0.59	0.40

3.2. Sensitivity analysis

The sensitivity analysis indicates robust performance and ranking of the three cases, despite uncertainties in parameter values. The energy ratios, total primary energy inputs, and net energy yields fluctuate by at most 34%, 38%, and 2%, respectively, see Fig. S4.1 in the Supplementary material. Energy use in ammonia production and fuel consumption rates have a considerable influence on energy ratios but not on net energy yields. Although the studied production systems depend on the use of many machines and implements with highly uncertain embodied energy, that parameter does not affect the results significantly. More information is available in the Supplementary material, Section S4.4.

4. Discussion

4.1. Comparison to other studies

Table 6 presents the results from a selection of similar studies identified in a literature review. Our results are well within the (wide) range of results from other studies: net yields are between 62 and 321 GJ ha^{-1} yr^{-1}, and energy ratios are between 10 and 124. Variations in results among studies are not surprising considering differences in goal, scope, data, and methods used (which also complicates comparisons). According to Börjesson [41], variations in results among studies are due to differences in geographical location (related to soil properties, climate, etc.), cultivation practices (use of machinery, level of fertilization, etc.), yield levels, transport of materials (means, distances), data sources, system boundaries and allocation methods. Djomo et al. [39] identified three main parameters responsible for the diverging results among studies: fertilization (amounts and type), harvesting method, and yield level.

All studies (including this) that have considered different levels of N fertilization report that a higher level of N fertilization is associated with lower energy ratios and – except one case in Boehmel et al. [37] – higher net energy yields. However, the magnitude of the effect varies

Table 6
Average annual net energy yields (the gross energy yield minus the total primary energy input, divided by the plantation lifespan) and energy ratios (the dimensionless ratio between the gross energy yield and total primary energy input) in energy analyses of willow production. The system boundaries are approximately similar in all studies (cradle-to-farm gate). N = nitrogen; LHV/HHV = lower/higher heating value.

Reference	Country	Average annual net energy yield ($GJ\,ha^{-1}\,yr^{-1}$)	Energy ratio (-)	N fertilization	Comments
This study	Sweden	86/133/175	47/32/19	Three N fertilization levels were considered: 0, 40, and 140 $kg\,N\,ha^{-1}\,yr^{-1}$ (see Table 1).	Energy yields and ratios refer to willow grown with no N fertilization (N-zero), a medium level of N fertilization (N-medium) and a high level of N fertilization (N-high), respectively.
Boehmel et al. [37]	Germany	257/243/263	104/82/76	Three N fertilization levels were considered: 0, 13.3, and 26.7 $kg\,N\,ha^{-1}\,yr^{-1}$ applied for 3 years.	LHVs were used and only fossil energy inputs were included. Model study based on empirical data from a 4-year field trial in southwestern Germany with the willow clone Tora. The model farm has a lifespan of 16 years. Energy yields and ratios (calculated based on data presented in the paper) refer to willow fertilized with 0, 13.3, and 26.7 $kg\,N\,ha^{-1}\,yr^{-1}$, respectively.
Buonocore et al. [38]	Sweden	N/A	13	No information about the use of fertilizers is available.	Only fossil energy inputs were included in this "embodied energy analysis." Model study based on empirical data from the Enköping bioenergy production system which includes 100 ha of willow plantations. The energy ratio refers to the willow farming subsystem.
Börjesson [26]	Sweden	172/321/317	21/36/26	Only one level of N fertilization in each time period is considered: 81 and 97 $kg\,N\,ha^{-1}\,yr^{-1}$ in the present and future scenario, respectively.	HHVs were used in this model study. Energy yields and ratios refer to 1) the situation in 1996, "the present," and 2) the situation in 2015, "an estimated future situation," with fossil-fuel-based energy inputs, and 3) the situation in 2015 with biomass-based energy inputs.
Börjesson [6]	Sweden	ca. 90–173 (average 128)	ca. 11–28 (average 20)	No information about the use of fertilizers is available.	HHVs were used in this model study based on data from the literature and statistics. Primary energy is considered and includes direct and indirect energy inputs. Energy yield and ratio values are based in part on visual inspection of figures in the report, hence approximate. Six Swedish regions were studied; ranges depend on region (production is generally more favourable in the south).
Börjesson and Tufvesson [29]	Sweden	173	24	Fertilizers are applied at a rate of 80 $kg\,N\,ha^{-1}\,yr^{-1}$.	HHVs were used in this model study of current cultivation practices in northern Europe. Willow is harvested every 4 years, over a total duration of, on average, 24 years. Primary energy is considered and include both direct and indirect energy inputs. The net energy yield was calculated based on data presented in the paper.
Djomo et al., [39]	Various, see comments	149–243 (results from 7 studies)	16–79 (results from 11 studies)	A majority of the reviewed studies include fertilization, but information about application levels is not available.	Review study; results are from the reviewed studies and refer to cradle-to-farm gate system boundaries. The studies reviewed are from Sweden (four studies, published between 1995 and 1997), England, Germany, Belgium, the Netherlands, Ireland, and the US. Net energy yields were calculated based on data presented in the paper.
González-García et al. [27]	Sweden	190	25	The application level is on average 54 $kg\,N\,ha^{-1}\,yr^{-1}$ (in total 1070 $kg\,N\,ha^{-1}$ during 20 years).	LHVs were used in this model study of a short rotation coppice system harvested every 4 years over a total duration of 20 years. The net energy yield was calculated based on data in the paper.

(*continued on next page*)

Table 6 (*continued*)

Reference	Country	Average annual net energy yield (GJ ha^{-1} yr^{-1})	Energy ratio (-)	N fertilization	Comments
González-García et al. [28]	Sweden	75/132	34/23	Two N fertilization levels were considered: 0 and 51 kg N ha^{-1} yr^{-1}, on average (in total 1070 kg N ha^{-1} during 21 years).	LHVs were used in this model study using yield data from a large sample of commercial plantations. Energy yields and ratios refer to an unfertilized and a fertilized case, respectively. Net energy yields were calculated based on data presented in the paper.
Heller et al. [40]	USA	N/A	55/ca. 39–58/ 45–80	Sensitivity analysis showed that energy ratios ranged between ca. 39 and 58 when the N application rate ranged between 300 and 48 kg N ha^{-1} per cutting cycle (≈100 and 16 kg N ha^{-1} yr^{-1}, respectively). The base case received 100 kg N ha^{-1} per cutting cycle (≈ 33 kg N ha^{-1} yr^{-1}).	Only fossil energy inputs were included in this model study based on field data collected from a 65 ha farm in western New York State. The biomass is harvested 7 times during 23 years; each cutting cycle is 3 years. Energy yields and ratios refer to 1) the base case, 2) results for different N application levels (the higher the N application rate, the lower the energy ratio), and 3) results for N applied in different forms. The base case represents current practices in New York State.
Scholz and Ellerbrock [42]	Germany	62/80/85	124/17/10	Three different levels of N fertilization were tested: 0, 75, and 150 kg N ha^{-1} applied once (≈ 0, 12.5, and 25 kg N ha^{-1} yr^{-1}, respectively).	Study based on data from a 6-year field trial with willow managed as short-rotation coppice and an undersown crop (12,000 plants ha^{-1}). Net energy yields and energy ratios were calculated based on data obtained by visual inspection of a figure in the paper, hence are approximate. Energy yields and ratios refer to willow fertilized with 0, 75, and 150 kg N ha^{-1}, respectively.

considerably, which is to be expected considering the different rates of N application, input data, assessment methods, etc. For example, Heller et al. [40] used sensitivity analysis and a model that predicts the yield response to N fertilization, while Boehmel et al. [37] and Scholz and Ellerbrock [42] used field trials to determine the yield response to fertilization.

The management operations and/or material inputs that contribute most to the total primary energy inputs align well with corresponding results in similar studies compiled by Djomo et al. [39], see Table 7. Only transport and fertilization stand out. Our results are relatively high for transport, while for fertilization they are low for N-zero and high for N-high.

4.2. Improvement options

Willow yields and energy inputs associated with N fertilization and biomass transport were identified as important determinants of energy performance. Current developments in the transport sector suggest that major improvements in fuel-use efficiency are possible. In addition, improvements in logistical planning and driving patterns can also contribute to reducing the energy inputs associated with transport.

Energy performance can be improved by using high-yielding willow clones, which are better adapted to the local climate and more responsive to fertilization. Willow has been bred in Sweden since the late 1970s, at the Swedish University of Agricultural Sciences, Svalöf Weibull AB, and Lantmännen Agroenergi AB [43]. The program at Svalöf Weibull AB focused mainly on developing high-yielding clones but also clones with tolerance against frost and mechanical operations, leaf rust resistance, erect growth, and bark that grazing animals avoid [44], all of which are factors that indirectly benefit biomass production. Swedish plant breeding programs have already contributed to increasing the average yield by about 50% compared to previously grown varieties [45], and further improvements are possible. Rosenqvist et al. [18] estimated that future yields at Swedish willow plantations may be 40% higher compared to current plantations, as a result of continued breeding in combination with other factors.

Performance can also be improved by reducing the energy use in ammonia production, which varies greatly depending on process technology and energy feedstock (see the Supplementary material, Section S3.4). Energy efficient plants, typically based on natural gas steam reforming, consume between 35 and 38 GJ Mg^{-1} of ammonia. The most energy efficient plants currently available consume 28 GJ Mg^{-1} of ammonia in an autothermal reforming process that combines steam reforming with partial oxidation [46]. By comparison, typical heavy-oil-based and coal-based processes use 1.3 and 1.7 times more energy than gas-based processes, respectively [46]. Rafiqul et al. [47] presented an overview of technical measures that can improve the energy efficiency in ammonia production, such as avoidance of heat loss by insulation, improved catalysts, and better process integration. IEA [46] estimated that if the best available technologies were applied at all stages of ammonia production worldwide, energy savings of up to 20% could be achieved. However, saving potentials are lower in Europe, where some of most energy efficient plants in the world can be found [48].

GHG emissions are beyond the scope of this study, but the attention to energy performance is motivated in part by the implications for GHG performance. The GHG emissions associated with ammonia production can be reduced by adopting carbon capture and storage techniques or by using biomass or water as hydrogen feedstock instead of fossil resources [48]. Hydrogen can be obtained from biomass via gasification and from water via electrolysis; the GHG emissions associated with the latter depend strongly on how the electricity is produced [48]. The next generation of ammonia plants are based on either a high temperature nuclear reaction or a solid state ammonia synthesis, both of which are powered completely by electricity and can hence be made carbon neutral [48]. Ammonia production using electricity from renewable energy sources offers interesting opportunities for the future [49]. See, for example, Tallaksen et al. [50] and Ahlgren et al. [51,52] for

Table 7
Contributions to total primary energy input from categories of management operations and/or material inputs; results from this study and from other energy analyses of willow production compiled in the review by Djomo et al. [39]. A somewhat different categorization is used here compared to Fig. 2, in order to better match that used by Djomo et al. [39]. All fertilizers were, e.g., grouped together. N/A = not applicable. Numbers may not add up due to rounding.

Management operations and/or material inputs	Contribution to total primary energy input from category (%)			
	Results from this study			Results from other studies, compiled by, and adopted from, Djomo et al. [39]. n = number of studies
	N-high	N-medium	N-zero	
Cuttings for planting	3	7	17	2–9 (n = 7)
Field management operations incl. planting[a]	1	2	5	2–8 (n = 9)
Production and application of herbicides	1	3	7	1–5 (n = 8)
Production and application of fertilizers[b]	72	51	13	36–59 (n = 8)
Energy embodied in machines and implements[c]	1	2	4	2–4 (n = 3)
Harvesting	7	11	16	8–43 (n = 9)
Transport[d]	12	20	30	2–15 (n = 5)
Field termination[e]	1	3	7	1–8 (n = 6)
Total	100	100	100	N/A

[a] Results from this study include plowing, harrowing, rolling, mechanical weeding, and planting. The corresponding category in Djomo et al. [39] is called "tillage/planting.".
[b] Results from this study include production and application of N, P and K fertilizers.
[c] The corresponding category in Djomo et al. [39] is called "capital equipment.".
[d] Results from this study include transport of wood chips to the bioenergy-conversion site and of machines and the empty wood-chip truck to the plantation.
[e] Results from this study include mulching and disc harrowing. The corresponding category in Djomo et al. [39] is called "grubbing up.".

assessments of N fertilizers produced using wind power, biomass, and biogas, respectively.

4.3. Implications for policy and future research

The results indicate that there is a trade-off between achieving a high net energy yield and achieving a high energy ratio, since N fertilization increases biomass growth but also contributes significantly to increasing the total primary energy inputs. The gross energy yields are more than 100% and 50% higher for N-high and N-medium, respectively, than for N-zero, while the total primary energy inputs are more than 5 and 2 times greater for N-high and N-medium, respectively, than for N-zero (Table 4).

General conclusions about the superiority of any specific case or level of fertilization are not supported by this study since it depends on several factors (not evaluated here) which vary geographically and over time, e.g., resource availability; potential environmental, social, and economic impacts of production as well as the (sometimes conflicting) interests of various stakeholders, such as land owners, farmers, policy-makers, and environmental groups. However, if land is the limiting resource, then a high net energy yield may be considered more important than a high energy ratio. In that case, the N-high system would be the most attractive option (disregarding other potential impacts, such as eutrophication).

Conversely, a low-input system with a higher energy ratio (N-zero) may seem preferable if access to energy is more limited than access to land. But since the net energy yield in itself influences the access to energy, the "optimal" system (from an energy point of view) is determined by the net energy response to additional energy inputs. However, since the total primary energy inputs correspond to just a few percent of the gross energy yields (Table 4), and the amount of arable land is limited, it might be considered more important to strive towards achieving high net energy yields than high energy ratios. In reality, farmers are not likely to be concerned with neither energy yields nor energy ratios, but they do consider factors that indirectly influence these measures, e.g., the costs of inputs, agricultural commodity prices, and legislation. Policy instruments can therefore be used to steer the production in the desired direction.

Which system, or intensity level, is most preferable in a given situation also depends on the existing agricultural policies and environmental legislation, e.g., bioenergy production targets, environmental objectives, and economic support to rural communities. Policies and legislation influence land use patterns, e.g., by influencing the availability of land, as well as management practices, e.g., the level of N fertilization. The Rural Development Committee of the Swedish Parliament states that rural Sweden will play a key role in bringing the country into a bio-based and fossil-free economy, and proposes measures aimed at supporting diversified, competitive, and sustainable rural economies [53]. The design and implementation of these measures will influence the future geographical distribution and balance between intensive and extensive willow production in Sweden (considered approximately equivalent to N-high and N-zero, respectively).

The outcome of energy balance studies can inform participatory processes engaging land owners, policy-makers, and other stakeholders in further developing and redefining goals and plans for biomass production in a broader landscape-management context. Such stakeholder processes also require information about the environmental, economic, and social aspects of production, which should be assessed in future studies. Future studies should also assess the conversion to secondary energy carriers and identify potential trade-offs and synergies between different political objectives and interests of various stakeholder groups in order to provide policy-makers and other decision-makers with adequate decision support and to guide future research.

4.4. Limitations of the study

This study only analyzed energy performance; important aspects beyond the scope of this study include environmental impacts associated with production, notably GHG emissions and eutrophication, as well as economic performance and social aspects of production (e.g., effects across stakeholder groups). The results show that a higher level of N fertilization is associated with higher net energy yields. However, increasing the N-fertilization level also increases GHG emissions (as long as fertilizers are produced using fossil fuels) and may also increase eutrophication and cause other negative environmental impacts. González-García et al. [28] found that willow fertilized with mineral N had greater impacts in terms of eutrophication, acidification, abiotic depletion, ozone layer depletion, human toxicity, freshwater, marine and terrestrial ecotoxicity, and photochemical oxidation than unfertilized willow.

Further, only the biomass production stage was studied; to better inform decision-makers, a complete assessment that considers the entire life cycle from primary production to end use, including conversion to secondary energy carriers (heat, electricity, or biofuels), is needed.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.rser.2018.05.045.

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