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Comparative economics of *Sida hermaphrodita* (L.) Rusby and *Silphium perfoliatum* L. as bioenergy crops in Europe

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ABSTRACT

The purpose of this research was to fill the identified gap on financial data of *Sida hermaphrodita* (L.) Rusby (Sida) and *Silphium perfoliatum* L. (Silphium), two perennial bioenergy crops that potentially provide a more sustainable alternative/complement to other bioenergy crops. Using discounted cash flow analysis, the Net Present Values of Sida and Silphium were compared to a rotation of other arable crops including maize, and the two energy crops of short rotation coppice and Miscanthus. The analysis was completed using the SidaTim analysis tool for the UK, Italy, Germany and Poland, producing a total of four independent models. The results showed that with no subsidies, cultivating Sida was unattractive in all four countries relative to other crop options. However, Silphium, was an economically viable option in each country. Both Sida and Silphium can offer greater environmental benefits than other arable crops, and the profitability of each crop would be further enhanced if additional payments for such public services were made to farmers, and if there were secure markets for the sale of the biomass. This study is the first comparative economic analysis in West and Central Europe of the two novel energy crops in comparison to more common energy crops and an arable rotation.

1. Introduction

In 2016, 196 governments signed the Paris Climate Change Agreement which committed them to limiting global temperature rises to no more than 2°C above pre-industrial revolution conditions [32]. To comply with the agreement, each country agreed to implement strategies and measures to offset and reduce their greenhouse gas (GHG) emissions. In June 2019, the UK announced the target to be carbon neutral for 2050, and it is supporting the replacement of fossil fuels with low-GHG emitting energy sources. Commonly cited bioenergy crops on agricultural land are short rotation coppice (SRC) species and Miscanthus (*Miscanthus x giganteus*), to produce woodchips and straw, and forage maize (*Zea mays* L.) to produce biogas. Two alternative crops that have been used in Eastern Europe are *Sida hermaphrodita* (L.) Rusby and *Silphium perfoliatum* L., referred as Sida and Silphium in the remainder of the article. From 2016 to 2019, within the SidaTim project, the performance of these two crops was studied in Italy, Germany, Poland, and the UK, including the results from the work presented in the current document.

Sida can be used to produce solid fuel for combustion if the plants are harvested at the end of winter when the shoots are still standing and have a moisture content of about 20% (own results). This species can also be harvested in summer as green biomass for anaerobic digestion [23]. Silphium is harvested in summer, when the dry matter content is about 30%, to produce biogas only. Compared to some other bioenergy crops, the environmental advantages of the two crops include increased production of pollen and nectar, reduced cultivation and hence increased soil carbon sequestration, and reduced levels of nitrogen and pesticide applications [10].

To answer for the lack of financial data and analysis associated with the production of Sida and Silphium, an economic model and posterior

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Abbreviations: CAP, Common Agricultural Policy; DM, Dry matter; FW, Fresh weight; GHG, Greenhouse gas; NPV, Net present value; ODT, Oven dry tonnes; SFP, Single Farm Payment; SRC, Short rotation coppice.

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Nomenclature

¤	Currency sign, unspecified currency (no units)

sensitivity analysis were developed for these two crops and were used to compare their profitability with an arable rotation and other major bioenergy crops. The aim of the article is to present the results obtained from the study.

2. Material and Methods

2.1. Economic model and financial analysis

The economic model for Sida and Silphium was developed following the net present value approach described by Graves *et al.* [18]. For comparison with annual arable crops, the gross margin was determined as the revenue (*R*: ¤ ha^{-1}) minus the variable costs (*V*: ¤ ha^{-1}) (Equation 1).

$$Gross\ margin = R - V \tag{1}$$

Since there were substantial differences in the machinery and labour demands between annual crop enterprises and long-term multi-annual enterprises such as Sida and Silphium, the comparison was made on a net margin basis, including labour and machinery costs as “assignable fixed costs” (*A*: ¤ ha^{-1}) (Equation 2).

$$Net\ margin = R - V - A \tag{2}$$

Because of their multi-annual nature, the financial performance of Sida and Silphium was evaluated using long-term financial analyses. Due to time preference for consumption of benefits in the short-term, the analyses discount future revenue streams using a discount factor which reflects a time preference for money. The discount rate depends on the purpose of the analysis and the economic circumstances of the population. The calculation of an aggregated discounted value that reflects the time preference for future income as a present value is referred to as net present value (NPV), calculated using the approach developed by Faustmann [15] (Equation 3):

$$NPV = \sum_{t=0}^{t=T} \frac{\left(R_t - V_t - A_t\right)}{(1 + i)^t} \tag{3}$$

where: *NPV* (¤ ha^{-1}) is the present value of aggregated future discounted net cash flow stream from year 0 to *t; T* is the time horizon in years; *R, V,* and A_t (¤ ha^{-1}) are respectively the revenue, variable costs, and assignable fixed costs in year *t*, and *i* is the discount rate.

2.2. Model implementation

The above equations were implemented in a spreadsheet model that was called the “SidaTim Economic Model” where input data include prices, grants, variable and fixed costs over a 16 year time horizon, for up to five arable crops and four energy crops on a one hectare scale. Starting with crop yields and inputs, the economic model was developed as a Microsoft Excel workbook including separate worksheets for the four participating countries (UK, Italy, Germany, and Poland). An introductory page explains how the model is organised and the sources of the input data. Then, the annual margins and the discounted cash flows are calculated, obtaining the NPV. Additionally, the infinite NPV (NPV_i) and the Equivalent Annual Value (*EAV*) are determined (Equation 4 and Equation 5).

$$NPV_i = NPV * \left((1+i)^T / \left((1+i)^T\right) - 1\right) \tag{4}$$

$$EAV = NPV_i / i \tag{5}$$

2.3. Selection of the case study sites

Four sites in the UK, Italy, Germany and Poland were selected where yield data for Sida and Silphium were available. In 2016, experiments were established in the north of Italy (Casale Monferrato), north Germany (Werlte), and north-western Poland (Lipnik) (Table 1). In the UK, the experiment was set in 2017 in the East of England (Silsoe, Bedfordshire). Mean air temperature at the sites ranged from 8.5-9.9°C in Germany, Poland, and the UK, to 12.5°C in Italy. Rainfall ranged from 555 mm in Poland to 784 mm in Italy [13].

2.4. Crop yields

For each site, yield profiles were derived for Miscanthus, SRC (willow in the UK, poplar and willow in Italy, Germany and Poland), Sida and Silphium (Table 2). The same Miscanthus yield profile was assumed at each site reaching a plateau of 12.5 t ha^{-1} [3] at four years after planting. In north Italy, it was considered that the first SRC harvest takes place in year 2 with a dry matter (DM) harvest of 26 t DM ha^{-1} every two years [5,24]. In Poland, Germany and the UK, the first harvest of the SRC happens in year 4, with yields of 30 t DM ha^{-1} in the UK [1] and Germany [22], and 25 t DM ha^{-1} in Poland [8]. Sida is harvested each year while Silphium is initially harvested in year 2 and then on an annual basis. For Italy, the estimated mature yields of Sida and Silphium were 10.0 and 15.0 t DM ha^{-1} y^{-1} [14]. The equivalent annual mature yields of Sida and Silphium at the other three sites were 11.6 t DM ha^{-1} and 16.3 t DM ha^{-1} (own results). The plateau yield of each crop was assumed to continue until year 16.

A common bioenergy crop typically grown in a rotation is forage maize. The assumed rotation in the UK was wheat (*Triticum aestivum* L.), sugar beet (*Beta vulgaris* L. subsp. *vulgaris* ‘altissima’), maize, oilseed rape (OSR) (*Brassica napus* subsp. *napus*), and oats (*Avena sativa*) (Table 3). In Italy, the selected arable crops were wheat, soya (*Glycine max* (L.) Merr.), sunflower (*Helianthus annus* L.), OSR, and maize. In Germany the sequence was wheat, sugar beet, maize, OSR and oats. In Poland the rotation was barley (*Hordeum vulgare* L.), OSR, wheat, sugar beet, and maize. The yields in the UK were mainly derived from the ©John Nix Pocket Book for Farm Management [2]. For Italy, Germany and Poland data was extracted from online websites, country-specific publications, and personal communication with experts.

2.5. Financial data and costs

Country-specific currencies were used in the analysis to keep it directly relevant to the corresponding countries and local stakeholders. The conversion rate applied for Italy and Germany, converting Pound Sterling (GBP) into Euros was 1.13 €/£ [22], and the conversion rate

Table 1
Location of the four sites in the four countries and description of characteristic soil, temperature and rainfall.

Site	Latitude and longitude	Altitude (m)	Soil type	Mean air temp. (°C)	Mean annual rainfall (mm)
Casale Monferrato (IT)	45.13°N; 8.51°E	116	Sandy loam	12.5	784
Werlte (DE)	52.85°N; 7.67°E	34	Sand	9.0	768
Lipnik (PL)	53.20°N; 14.58°E	47	Sand	8.5	555
Silsoe (UK)	52.07°N; 0.63°W	50	Sandy loam	9.9	657

Table 2
Assumed annual yield profiles (t DM ha^{-1}) of the perennial bioenergy crops in the four case studies considered.

	Miscanthus	SRC			Sida		Silphium	
Year	All sites	Italy	Poland	Germany and UK	Italy	Other sites	Italy	Other sites
1	0.6				1.8	2.1	0.0	0.0
2	3.9	26.0			7.1	8.3	9.1	9.9
3	11.1				9.4	10.9	13.5	14.7
4	12.5	26.0	25.0	30.0	10.0	11.6	14.5	15.7
5	12.5				10.0	11.6	15.0	16.3
6	12.5	26.0			10.0	11.6	15.0	16.3
7	12.5		25.0	30.0	10.0	11.6	15.0	16.3
…								
16	12.5	26.0	25.0	30.0	10.0	11.6	15.0	16.3

Table 3
Assumed annual yields (t ha^{-1}) of the annual crops at the five sites.

	UK	Italy	Germany	Poland
Wheat	8.3 (i)	5.5	7.5	4.6
Sugar beet (FW)	78.0 (i)	-	63.1	56.8
Sunflower	-	2.1	-	-
Forage maize (DM)	12.0 (ii)	9.4	8.1	12.0
Oilseed rape	3.5 (i)	2.6	3.3	3.5
Soya	-	3.1	-	-
Oats	6.3 (i)	-	4.1	-
Barley	-	-	-	2.5
Reference	(i) ABC Ltd [2](ii) ABC Ltd [1]	CREA [9]	Statista.com [28]	Bury [8]

[a] FW = Fresh weight

Table 4
Assumed value of crops at the four sites.

	UK (£ t^{-1})	Italy (€ t^{-1})	Germany (€ t^{-1})	Poland (PLN t^{-1})
Biomass (ODT)	55.0	43.8	72.0	269.5
Forage maize (FW)	107.1 (i)	94.3	182.8	724.0
Wheat	162.0 (ii)	210.0	193.7	867.0
Oats	140.0 (ii)	-	154.8	-
OSR	335.0 (ii)	197.0	345.1	1645.0
Sugar beet	27.2 (ii)	-	26.0	120.0
Sunflower	-	235.6	-	-
Soya	-	310.8	-	-
Reference	(i) BASF SE [6](ii) ABC Ltd [2]	CREA [9]	Statista.com [28]	Bury [8]

applied for Poland was 4.90 PLN/£ [8]. The price of biomass oven-dry-tonnes (ODT) was assumed to be the same for all energy crops within a country, equal to £ 55 t^{-1} in the UK, € 43.8 t^{-1} in Italy, € 72.0 t^{-1} [22] in Germany, and PLN 269.5 t^{-1} in Poland (Table 4). The values of the arable crops were derived from published reports. In addition, agricultural production in each country can receive single farm payments (SFP) which amounted to £ 220 ha^{-1} in the UK in 2019 [2]. The Common Agricultural Policy (CAP) receipts for the crops in Italy, Germany, and Poland were respectively € 330 ha^{-1}, € 176 ha^{-1}, and PLN 472 ha^{-1}.

Management data and input data for the perennial bioenergy crops in each country were collected from secondary data sources and personal communication. The initial costs of establishment included ground preparation, planting out, plant materials, fertilising and spraying costs. The planting materials were cuttings for SRC, rhizomes for Miscanthus, seedlings for Sida, and seeds for Silphium. Plant protection was applied in each country during the establishment year and years 2-3 for bioenergy crops. Mineral fertilisers were applied during establishment, and on a recurring basis after every harvest to maintain soil nutrient status at a similar level to the arable crops. For illustration, the assumptions for the UK are shown in Table 5; details of other sites are presented in Appendix A A.2. Inputs for bioenergy crops.

The management costs of the arable crops were taken from a range of sources including farm management handbooks, and regional, national, and European level statistical publications and databases available for the UK, Italy, Germany, and Poland. Variable costs included use of seeds, fertilizers, and spraying for pests, diseases and weed management. Fixed costs included use of standard approaches and costs for ploughing and seedbed preparation, followed by drilling, and fertiliser and spray operations. Management also included the costs of combine harvesting and carting for grain and straw collection.

3. Results and Discussion

3.1. Yields and price of biomass

Yields and crop prices are important determinants of crop profitability. The mature yields of Sida and Silphium in this study were based on experimental results and in line with yields reported elsewhere.

The profitability of Sida is currently limited by its relatively low yields when harvested for solid fuel and high establishment costs. When Sida was harvested at the end of winter for the production of solid fuel, the mean yields in the participating experimental sites on the SidaTim project ranged from 6.2 to 10.6 t DM ha^{-1} in the third year of cultivation [7]. The mean yields of Sida when it was harvested in summer as green biomass for biogas obtained in the SidaTim project ranged from 7.6 to 15.1 t DM ha^{-1} [7], showing that commercial plantations could potentially produce substantial amounts of biomass.

When compared to other arable and energy crops in the present study, Silphium is a highly profitable and competitive crop. The theoretical mature yields used for the economic model of 16.3 t DM ha^{-1}

Table 5

Assumed costs for SRC, Miscanthus, *Sida hermaphrodita* (L.) Rusby, and *Silphium perfoliatum* L. in the UK.

Establishment costs		SRC	Miscanthus	Sida	Silphium
Planting material [a]	(£ ha^{-1})	750.0	1190.0	4361.0	1312.8
Planting [a]	(£ ha^{-1})	300.0	350.0	126.3	45.0
Ground preparation	(£ ha^{-1})	200.0	180.0	180.0 (i)	180.0 (i)
Fertilisers [a]	(£ ha^{-1})	126.3	117.7	162.0	177.7
Fertiliser application [a]	(£ ha^{-1})	16.1	16.1	16.1	16.1
Sprays	(£ ha^{-1})	200.0	120.0	120.0 (i)	120.0 (i)
Spray application [a]	(£ ha^{-1})	40.3	40.3	20.2	20.2
Mechanical weeding [a]	(£ ha^{-1})	-	-	120.8	120.8
Cutback end first year	(£ ha^{-1})	50.0	20.0 (ii)	20.0 (i)	20.0 (i)
Recurring costs					
Mechanical weeding [a]	(£ ha^{-1})	-	-	161.0	161.0
Fertilisers [a]	(£ ha^{-1})	126.3	117.7	162.0	177.7
Fertiliser application [a]	(£ ha^{-1})	16.1	16.1	16.1	16.1
Sprays [a]	(£ ha^{-1})	100.0 (iii)	60.0 (iii)	-	-
Spray application [a]	(£ ha^{-1})	40.3	40.3	-	-
Harvesting	(£ ha^{-1})	450.0	-	100.0 (iv)	-
Mowing and baling	(£ ha^{-1})	-	240.7 (v)	-	-
Harvesting and clamping	(£ ha^{-1})	-	-	-	175.0 (vi)
Decommissioning	(£ ha^{-1})	170.0 (vii)	170.0 (vii)^{i}	170.0 (vii)	170.0 (vii)

Notes: Default 4% discount rate.

(i) Assumed same as Miscanthus; (ii) [2]; (iii) Assumed half cost of sprays (establishment); (iv) Assumed same as forage maize harvesting only; (v) [33]; (vi) Assumed same as forage maize full harvesting operation; (vii) [25];

- Ground preparation costs: SRC and Miscanthus 5.0 h ha^{-1} and Silphium 6.0 h ha^{-1}.
- Planting material costs: considering Sida at € 350 per 1000 seedlings [20] and 14000 seedlings per ha [11]; Silphium at € 295 per 500 g seeds and 2.5 kg seeds per ha [12].
- Planting costs: Sida same cost as potato planting at £ 126.29 ha^{-1} and 1.1 h ha^{-1} (assumed same time as wheat); Silphium same cost and time as forage maize [1].
- Fertiliser costs (establishment): calculated using cost of N, P_2O_5, K_2O (£ kg^{-1}) of 0.65, 0.64, 0.45 and fertilising rates for SRC – 90, 55, 72 and Miscanthus – 84, 14, 120 from AHDB [4]; Sida – 100, 92, 84 and Silphium – 120, 92, 90 calculated from Cumplido-Marin *et al.* [10].
- Fertiliser application costs (establishment): all crops x1 extra for variable rate application at £ 16.07 ha^{-1} and 1.2 h ha^{-1} (assumed same time as wheat).
- Spray application costs (establishment): considering x4 spraying (based on 200 l/ha & 24m boom) at £ 10.08 ha^{-1} and 0.3 h ha^{-1} for SRC and Miscanthus and x2 spraying (based on 200 l/ha & 24m boom) at £ 10.08 ha^{-1} and 0.3 h ha^{-1} for Sida and Silphium.
- Mechanical weeding costs (establishment): Sida and Silphium – considering x3 same rate as tractor + post knocker + man (per hour) at £ 40.25 ha^{-1} and 0.3 h ha^{-1} (assumed same time as wheat spraying).
- Mechanical weeding costs (recurring): Sida and Silphium – considering x4 same rate as tractor + post knocker + man (per hour) at £ 40.25 ha^{-1} and 0.3 h ha^{-1} (assumed same time as wheat spraying).
- Fertiliser costs (recurring): calculated using cost of N, P_2O_5, K_2O (£ kg^{-1}) of 0.65, 0.64, 0.45 and fertilising rates for SRC – 90, 55, 72 and Miscanthus – 84, 14, 120 from AHDB [4]; Sida – 100, 92, 84 and Silphium – 120, 92, 90 calculated from Cumplido-Marin *et al.* [10], only applied on harvest years.
- Fertiliser application costs (recurring): all crops x1 extra for variable rate application at £ 16.07 ha^{-1} and 0.3 h ha^{-1} (assumed same time as wheat), only applied on harvest years.
- Spray application costs (recurring): considering x4 spraying (based on 200 l/ha & 24m boom) at £ 10.08 ha^{-1} 0.3 h ha^{-1} for SRC and Miscanthus for years 2-3.

[a] Costs calculated using SidaTim model and the following raw data, obtained by default from ABC Ltd [1] unless indicated otherwise:

for the UK, Germany and Poland, and 15.0 t DM ha^{-1} for Italy, correspond with the experimental results obtained in the SidaTim project, where mean yields ranged from 14.3 to 18.0 t DM ha^{-1} in the third year.

A major assumption of the model, is that once the plantations reach maturity, the yields remain exactly constant for the rest of the rotation. In reality, however, this will not be the case. Assuming the establishment was successful and management is consistent, yields will vary annually responding to climatic conditions. To determine the accuracy of the model regarding annual variation in yields due to climatic conditions, one would need to collect annual yields over the maturity period of the crops and compare that recorded mean with the mean used as input for the model.

The price of biomass has a great impact on the profitability of energy crops. The present study considered a relatively conservative price of £ 55 t^{-1} DM for all energy crops, as indicated by ABC Ltd [1] for SRC and Miscanthus. If the biomass obtained from Sida and Silphium was higher, then the profitability of both crops would rise. We can observe in the UK sensitivity analysis that when prices are increased by 100% to £ 110 t^{-1} DM, the NPVs (with grants) would rise to £ 8079 ha^{-1} and £ 15219 ha^{-1} for Sida and Silphium respectively. A price of £ 110 t^{-1} DM is certainly plausible as the price achieved by forage maize supplied to the biogas industry (£ 35-40 per tonne at 35% DM [6] is equivalent to £ 107 t^{-1} DM).

Market prices of Sida and Silphium in Italy, Germany and Poland are about € 45 t^{-1}, € 72 t^{-1}, and € 59 t^{-1} respectively, prices being paid to farmers in the three different countries, which reflect the variation in the value of the same product between individual countries. Within the sensitivity analysis, the relatively conservative price of £ 55 (€ 61) t^{-1} DM was chosen as the default, but in reality the price of Sida and Silphium would depend on the agreed price in the biomass contract.

3.2. Net Present Values

The predicted NPVs for the perennial crops and the arable rotations over 16 years, at a default discount rate of 4%, in the UK, Italy, Germany, and Poland with/without CAP or SFP are shown in Table 6.

Studies of the profitability of energy crops are uncommon and the results vary greatly. Research of Sida and Silphium has mainly focussed

Table 6
The net present value (NPV), for the arable rotation and four energy crops with and without the single farm payment (SFP) in the UK, Italy, Germany, and Poland. The time horizon used was 16 years and the discount rate was 4%. The most profitable crop in each location without grants is shown in bold.

			Rotation	SRC	Miscanthus	Sida	Silphium
UK	NPV without SFP	(£ ha^{-1})	1927	1765	2296	-1591	**3031**
	NPV with SFP	(£ ha^{-1})	4593	4432	4962	1075	5697
Italy	NPV without CAP	(€ ha^{-1})	-3392	**766**	-1501	-4875	-734
	NPV with CAP	(€ ha^{-1})	877	3665	2769	-606	3536
Germany	NPV without CAP	(€ ha^{-1})	-641	2188	2471	-510	**5241**
	NPV with CAP	(€ ha^{-1})	1492	4321	4604	1622	7373
Poland	NPV without CAP	(PLN ha^{-1})	-6602	5407	-54597	-16022	**9458**
	NPV with CAP	(PLN ha^{-1})	886	11122	-48881	-10306	15173

on their production with few studies looking at their production costs. To assess the validity of the SidaTim model and the results obtained for Sida and Silphium, we considered it necessary to at least compare the results from the model for SRC and Miscanthus with results by other researchers.

Our reported profitability of SRC coppice in the UK assuming no subsidies of £ 1765 ha^{-1} (*i.e.*, € 1932 ha^{-1}) at 4% discount rate over 16 years is in line with the results reported elsewhere. For a study in Wales, Heaton *et al.* [19] observed the NPV of SRC ranged from £ 979 to £ 2956 ha^{-1} with yields of 6 and 12 t DM ha^{-1} y^{-1} respectively (at 4% discount rate). In Croatia, Posavec *et al.*, [26] obtained a NPV of € 1055 ha^{-1} at 7% discount rate. Styles *et al.*, [30] analysed the profitability of SRC and Miscanthus in Ireland under different scenarios, calculating EAVs of € 211-270 and € 326-383 ha^{-1} y^{-1} respectively at 5% discount rate, mid-production conditions and funding of € 125 ha^{-1} y^{-1}. Feeding exactly the same grants in the SidaTim model for SRC and Miscanthus in the UK, the results are equivalent to € 295 and € 346 ha^{-1} y^{-1} respectively, at 4% discount rate, within the above given ranges. On the other hand, the results obtained by Fradj and Jayet [16] for Miscanthus vary greatly from the SidaTim model results. For a medium yield scenario (12-18 t DM), NPVs ranged from € 500 to € 800, as opposed to the € 2543 ha^{-1} (£ 2296 ha^{-1}) we obtained.

Establishment costs are crucial in determining the profitability of energy costs. On average, from their real operation in the UK, it costs Terravesta [31] £ 1530 ha^{-1} (€ 1805 ha^{-1}) to establish 1 ha of Miscanthus (personal communication). Comparing this to the establishment costs calculated in the SidaTim model (£ 1994 ha^{-1} / € 2352 ha^{-1}), we can conclude that our model slightly overestimated the costs of establishment for Miscanthus. Within the SidaTim model, the high establishment costs for Sida, which were obtained from a plant nursery in Germany, make the profitability of Sida low compared to other options. However, the establishment costs in the literature shows wide variability ranging from € 1860 to € 2715 ha^{-1} [27] through to € 5000 ha^{-1} [17], € 8096 ha^{-1} ([29]b), compared to € 5658 ha^{-1} (£ 5106 ha^{-1}) used in the SidaTim model. If treated seeds with a high germination percentage became available, the costs of establishment of Sida could be in the region of € 1159 ha^{-1} [29].

3.3. *Discounted cash flow values*

The cumulative cash flow of the perennial crops in the UK, Italy, and Germany (Figure 1) show a negative balance for the initial five to eight years; the arable rotation provides a positive return from the first year. However, by the end of the rotation, the predicted cumulative cash flow of the perennial crops tends to be similar or greater than that from the arable rotation with two exceptions. The cumulative cash flow of Sida in each country remained below or similar to the arable rotation after 16 years and Miscanthus values are extremely negative in Poland due to high establishment costs.

3.4. *Sensitivity analyses*

Under the default assumptions, the sensitivity analyses describe the variation of the NPV of Sida, Silphium, SRC, Miscanthus, forage maize, and the arable rotation to systematic alterations in prices, costs, and discount rate. The data underlying these results are shown in Appendix A A.4. Sensitivity analyses.

United Kingdom: Silphium was the most profitable system. However if crop prices were assumed to be 15% or more higher than the default values, the annual crop rotation became the most profitable system (Figure 2). Conversely, if crop prices decreased by more than 50%, SRC and Miscanthus became more profitable than Silphium. Sida remained the least profitable option for the analysed increases in price, but became more profitable than the arable rotation and forage maize for decreases in price of more than 25% and 50%, respectively. As costs increased by more than 50%, Miscanthus became marginally more profitable than Silphium. As costs decreased 10-25%, forage maize was most profitable, whilst beyond a 35% decrease in costs, the arable rotation became most profitable. As costs changed, Sida was the least profitable option, except for increases in cost beyond 50% and decreases in cost beyond 70%. For the examined changes in discount rate, Silphium remained the most profitable crop, followed by Miscanthus, SRC, forage maize, and the arable rotation.

Italy: the SRC option was marginally more profitable than the Silphium option (Figure 3). As prices increased, Silphium remained marginally less profitable than SRC but converged with SRC and forage maize at 100% price increase. The arable rotation became most profitable when prices increased over 60%. As prices decreased over 50%, Silphium became marginally less profitable than Miscanthus. When costs increased, the profitability of Miscanthus was marginally lower than that of Silphium, almost converging at 100% increase. As costs decreased beyond 45%, the arable rotation option became the most profitable. The profitability of Sida turned positive as prices increased. As prices decreased, the NPV of Sida was higher than the NPV of forage maize and higher than the NPV of the arable rotation beyond a 25% price decrease. As costs increased, Sida was more profitable than the forage maize, and with cost increases greater than 25% it became more profitable than the arable rotation. As costs decreased, Sida remained the least profitable option. Sida was marginally more profitable than the forage maize as discount rates decreased and marginally less profitable than the arable rotation at other discount rates.

Germany: Silphium had the highest NPV and remained relatively robust to variations in price, costs, and discount rate (Figure 4). As prices increased beyond 40%, forage maize became more profitable than Silphium. As prices decreased beyond 60%, SRC became marginally more profitable than Silphium, and the profitability of Miscanthus converged with Silphium. Sida remained the least profitable option for the examined price increases. At any decrease in prices, Sida was more profitable than the arable rotation option and with price decreases of 50% or greater it was also more profitable than the forage maize option.

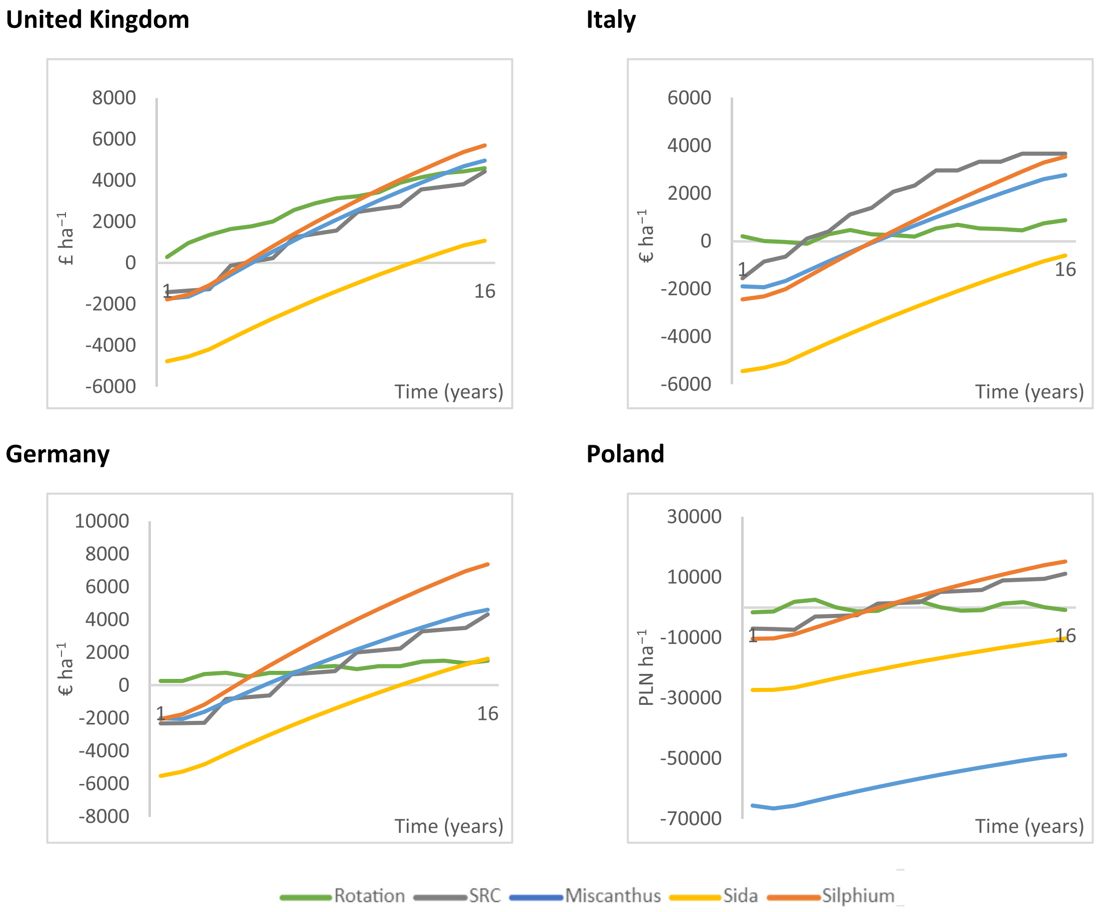

Fig. 1. Discounted cumulative net margins with grants included.

As costs increased, Silphium remained the most profitable crop and Sida was more profitable than the arable rotation and was marginally greater than the profitability of forage maize, when costs increased by 90% or more. As costs decreased more than 20%, forage maize became the most profitable option, and for decreases in costs over 50% the arable rotation became more profitable than Silphium. Sida remained the least profitable option for decreases in cost up to 60%. Beyond a decrease of 60% in costs, Sida became more profitable than SRC, converging in profitability with Miscanthus. The response to fluctuations in discount rate showed that lower discount rates favoured Silphium in particular. As discount rates increased towards 100%, the NPV of forage maize became increasingly more profitable, converging to almost the same value as Silphium. The arable rotation was consistently less profitable than Sida at lower discount rates, but its profitability converged and marginally overcame that of Sida as discount rates increased.

Poland: generally, forage maize was the most profitable and Miscanthus the least profitable option for any variation in price, costs, and discount rate (Figure 5). The NPV of Sida became positive for price increases over 30%. As prices decreased beyond 40%, SRC became the most profitable and the profitability of Silphium and Sida exceeded that of the rest of crops. When costs increased by 100%, the profitability of Silphium converged with the profitability of forage maize. For costs increases over 40% Sida became more profitable than the arable rotation. As costs decreased beyond 50%, the arable rotation became more profitable than Silphium. As costs decreased by over 60%, the Sida became marginally more profitable than SRC, converging with the profitability of Miscanthus at 100% costs decrease. As discount rates increased, forage maize profitability remained the highest, the NPV of the SRC option converged to almost the same as Silphium, and the NPV of Sida was marginally lower than the arable rotation but converged at 100% decrease.

3.5. Funding, support and extra income

The study demonstrates how funding affects the profitability of energy crops. Within this analysis we have assumed that agricultural bioenergy crops are fully eligible for single farm payments through the CAP. In addition, it could be argued that some bioenergy crops should be eligible for additional payments because of the ecosystem services that they provide. If crops like Sida and Silphium were granted an additional environmental services reward of £ 220 ha^{-1} y^{-1} (equal to the SFP generally provided to arable crops), their NPVs automatically would jump to £ 1075 and £ 5697 ha^{-1} respectively.

Alternatively, if the costs of establishment were fully funded, the NPVs of Sida and Silphium would be £ 3515 ha^{-1} and £ 5023 ha^{-1} without any further support. An alternative to government support is to secure additional income from related products. For example, Sida and Silphium crop income could be supplemented by the production of honey, producing about 230 and 450 kg ha^{-1} [21]. Considering the price of honey to be £ 20 kg^{-1}, this would amount to extra £ 4600 and £ 9000 ha^{-1} y^{-1} for Sida and Silphium respectively.

3.6. Environmental valuation

Given the challenge of maintaining global warming levels within the limits set by the Paris Agreement and the need to tackle related environmental challenges, such as the loss of pollinators and biodiversity in rural areas in general, there is a clear need to evaluate systems through a broader ecosystems perspective. This would allow cropping systems to

Fig. 2. Sensitivity of the NPV (over 16 years at 4% discount rate) of four bioenergy crops and an arable rotation including maize to changes in a) prices, b) yields, c) costs, and d) discount rates in the United Kingdom.

Fig. 3. Sensitivity analysis of the net present value (NPV) of different crops in Italy in relation to proportional changes in a) price, b) yields, c) total costs, and d) discount rates.

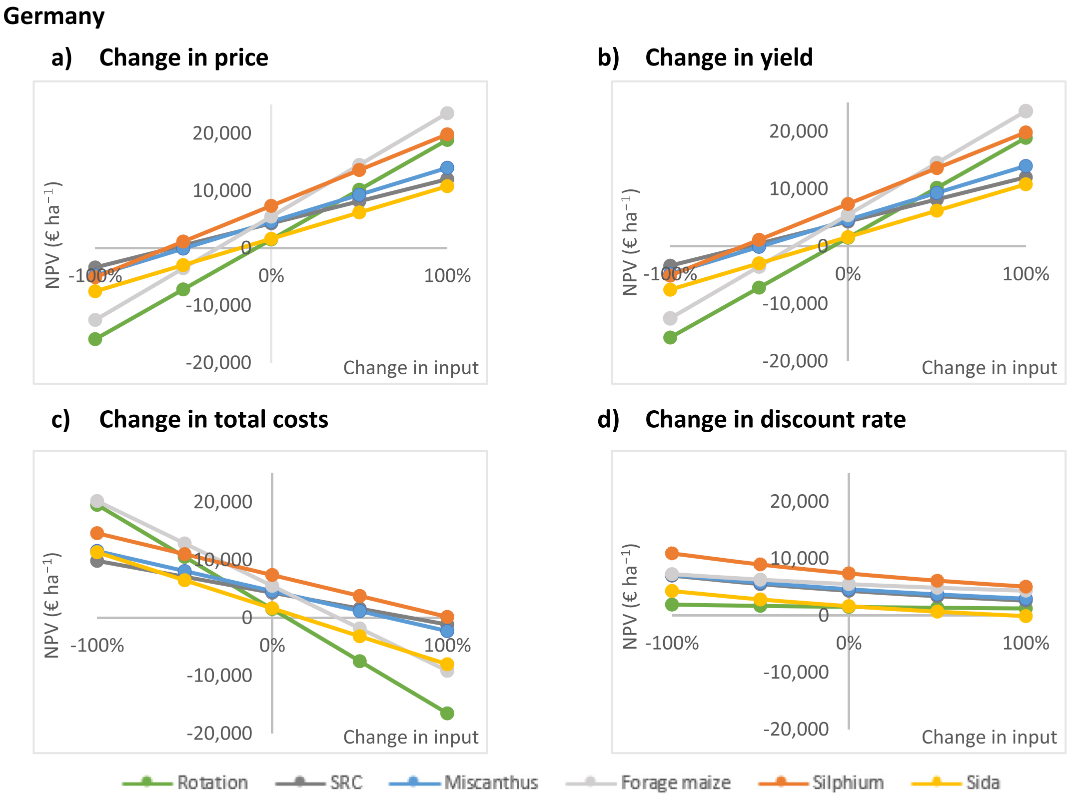

Fig. 4. Sensitivity analysis of the net present value (NPV) of different crops in Germany in relation to proportional changes in a) price, b) yields, c) total costs, and d) discount rates.

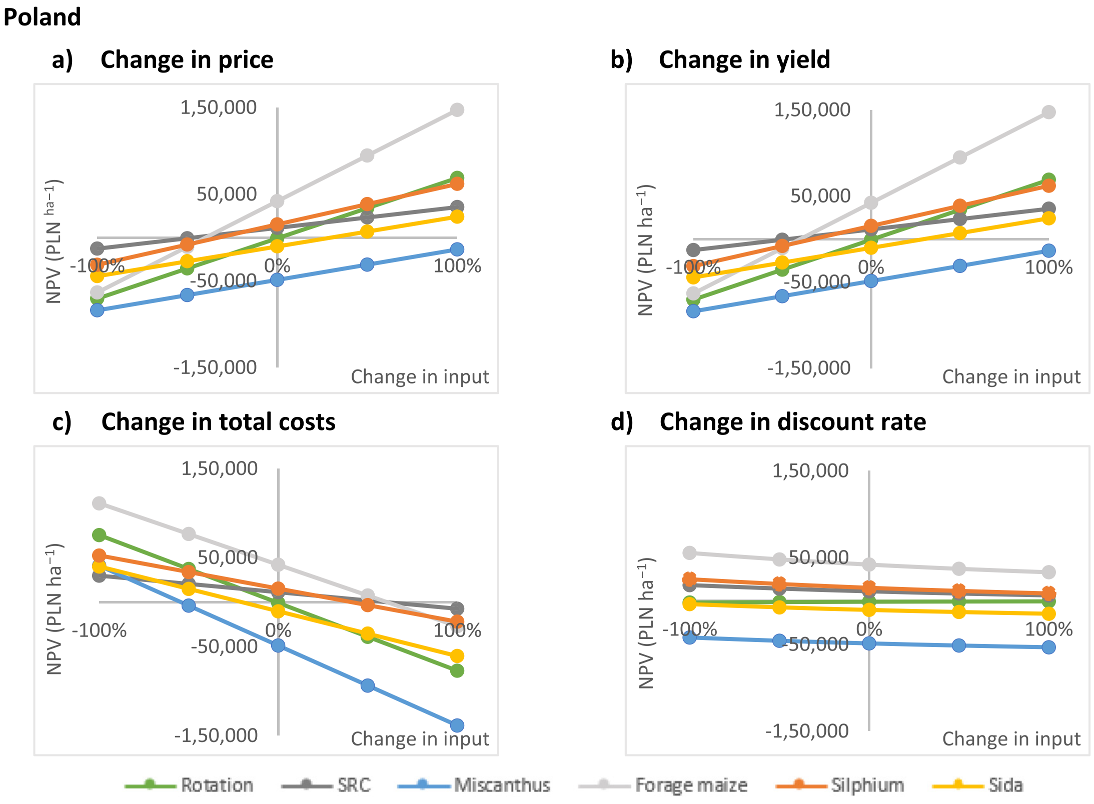

Fig. 5. Sensitivity analysis of the net present value (NPV) of different crops in Poland in relation to proportional changes in a) price, b) yields, c) total costs, and d) discount rates.

be compared on the basis of their broader environmental and social impacts, as well as on the basis of their financial profitability. Sida and Silphium would benefit from such evaluations, which could use approaches like life cycle assessment and environmental valuation to derive a more complete analysis of the benefits of these different systems.

3.7. Further research

The present financial study was carried out without accounting for irrigation as agricultural operation for any of the studied crops. Further research should include scenarios where irrigation is essential, like in more temperate and southern areas.

3.8. Relevance to the Energy Nexus Journal

The article is a clear example of the interdependencies and synergies between agriculture and the energy sector, presenting the results from a financial study conducted on two novel bioenergy crops that could be implemented into marginal/low quality agricultural land, potentially increasing farm sustainability, contributing to diversify and expand the bioeconomy, reducing GHG emissions, and providing diverse sources of income to farmers.

4. Conclusion

Without any grant payments, Silphium was the most profitable option in the UK, followed by Miscanthus, the arable rotation and SRC, whilst the profitability of Sida was negative. In Italy, SRC was the most profitable and only option with a positive NPV. In Germany, Silphium was most profitable, followed by Miscanthus and SRC, whilst both Sida and the arable rotation had negative NPVs. In Poland, Silphium was again the most profitable option, followed by SRC, whilst Miscanthus, Sida and the arable rotation had negative NPVs. When funding was included in the analysis, the profitability of all crops increased accordingly, turning most unprofitable options into profitable ones, except for the case of Sida in Italy, and Sida and Miscanthus in Poland. The profitability of Miscanthus in Poland was extremely negative because of the high establishment costs. The profitability of the arable rotation varied between countries, reflecting the differences in productivity, prices and costs.

The analysis suggests that given the assumptions made regarding input prices and costs in the United Kingdom, Italy, Germany, and Poland, Silphium could on the whole provide a profitable and highly competitive alternative to arable and energy crops to strengthen and support the bioeconomy. For Sida to be a profitable and viable crop, yields need to be above 12 t DM ha^{-1} and would greatly benefit from establishment grants or the development of a more successful establishment method using seed.

The sensitivity analysis suggested that, on the basis of the assumptions made, both Sida and Silphium were both profitable with subsidies and that large decreases in prices and increases in costs would be needed for the crops to show a negative financial return. Sida was generally outperformed by other crops in each of the four countries. In the UK, Silphium was less profitable than the forage and the arable rotation but out-performed the SRC and Miscanthus under favourable conditions. In Italy and Germany, Silphium was highly profitable and performed at a level that made it attractive as an alternative to an arable rotation and other energy crops. In Poland, the results showed that Silphium was generally less profitable than forage maize, but it outperformed the arable rotations and most of the other energy crop options.

The current study is based on the assumption that energy crops produce a stable yield throughout their mature life. In reality this may not be the case because especially perennial plantations can lose some of their productivity over the years, resulting in reduced yields or may be damaged by wildfires, major pests or diseases, or by wildlife. In the occurrence of such events, the productivity will also be reduced according to the extent of the damage and the cost of replacing the damaged areas or controlling external agents should be taken into consideration.

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Data availability

The full models for the four participating countries developed during the project can be accessed through Cranfield Online Research Data (CORD) repository system using the following link: https://doi.org/10.17862/cranfield.rd.18007136.v2.

Declaration of Competing Interest

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

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.nexus.2022.100084.

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