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Life Cycle Impact Assessment of Miscanthus Crop for Sustainable Household Heating in Serbia

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Abstract: This paper investigates the environmental impacts and energy benefits of the cultivation of Miscanthus (*Miscanthus* × *giganteus* Greef et Deu.), in order to initiate its use in sustainable household heating in the Republic of Serbia. Based on the analysis of available data regarding the use of agricultural machinery in Serbia, a Miscanthus supply chain is constructed and examined in detail, scrutinizing all relevant operations—from planting of rhizomes to thermal energy production. Results of the life cycle assessment identify the briquetting process as the most environmentally burdensome operation due to high electricity consumption and low productivity. It is concluded that an average yield of 23.5 t dry matter (d.m.) year^{-1} obtained from 1 ha of chernozem soil would have energy output:energy input (EO:EI) ratio of 51:1, and would release 365.5 gigajoules (GJ) of heat during combustion in a boiler. With this amount of energy, around 383 m^2 of a free-standing family house in Serbia can be heated annually. The same amount of energy is obtained by the combustion of 22 t of lignite or 23 t of wood logs. The substitution of lignite and wood with Miscanthus briquettes would lead to significant reduction of CO_2 equivalents (eq), SO_2 eq, P eq, N eq, 1,4 dichlorobenzene (1,4-DB) eq, Non-methane volatile organic compound (NMVOC), PM10 eq and U235 eq emissions. This designates Miscanthus as a more sustainable energy solution for household heating. In instances where more modern agricultural machinery is used, emission reduction is higher, except for CO_2 eq due to higher emission factors predicted for more powerful engines. Depending on Miscanthus' annual yield, the replacement of set-aside land with Miscanthus plantations result in carbon (C) sequestration from 0.08 t C ha^{-1} year^{-1} to 0.91 t C ha^{-1} year^{-1}. In a modern machinery scenario, C sequestration is only attainable when maximal Miscanthus yield is obtained. The combined use of machinery with different engine power is the best option for Miscanthus cultivation in Serbia.

Keywords: bioenergy; *Miscanthus giganteus*; life cycle assessment; household heating; soil organic carbon

1. Introduction

Population growth and improvements in living standards inevitably lead to a demand for higher energy, especially in the household sector. In the Republic of Serbia, the household sector accounts for approximately 36% of the total energy consumption; 58% of that share represents energy used for heating [1]. Considering the different heating systems applied, the District Heating System (DHS) has been applied in 22% households and Individual Heating Systems (IHS) in 78% households. Of the total number of IHS users, 21% have central heating systems and 57% use stoves that mostly use wood logs (72%) and coal (21%) [2]. The extensive use of wood logs, as compared to other fossil fuels, is due to low wood prices and proximity to forests, since most IHS users are located in rural areas. Considering coal consumption, 94% of the coal used in Serbia is domestically produced, while 6% is imported [3]. With regard to domestically produced coal, lignite accounts for 98% and higher-quality coals 2% [4]. These fuels are being used in low-efficiency stoves, where the emission of pollutants is disproportionally high, when compared to the energy provided [4].

By adopting the EU Renewable Energy Directive 2009/28/EC, Serbia has obliged to increase its use of renewable energy sources (RES) in total energy consumption by 27% until 2020 [3,5]. Over the last six years, RES share in final energy consumption in Serbia was only around 12.6%, showing a slight decline [3,5]. Considering the structure of RES, the highest contribution comes from biomass (55%), followed by hydropower (44.5%); while biogas, wind, solar and geothermal energy contribute a combined total of only 0.5%. Biomass is the most abundant and important renewable energy source in the Republic of Serbia. In addition to obtaining biomass from agricultural residues, liquid manure and wood [4], efforts are being made towards a higher inclusion of bioenergy crops [6].

Miscanthus (*Miscanthus* × *giganteus* Greef et Deu.) is a perennial bioenergy crop, the use of which as an RES has attracted worldwide attention due to its high yields, good biomass combustion quality, and lower greenhouse gasses (GHG) emissions compared to fossil fuels [7–19]. *Miscanthus* × *giganteus* is a triploid hybrid from two Miscanthus species (*M. sinensis* Andersson and *M. sacchariflorus* (Maxim.) Franch.) [20], a C4 plant type with lifespan of about 15 to 20 years [21]. The annual yield of Miscanthus is 10–25 t d.m. ha^{-1} in central and northern Europe, or up to 30 t d.m. ha^{-1} in southern Europe due to differences in the duration of growing seasons [10,22,23]. Apart from a dependency on different climatic conditions, Miscanthus yield is also influenced by soil type, planting density, fertilization, irrigation, and harvesting time [24]. Compared to winter harvest, autumn provides higher yields, but a lower quality of biomass for combustion due to a higher concentration of ash, minerals, and water [23,25]. The energy content of 1 tonne of dry Miscanthus is 15–19 gigajoules (GJ) [14,23,25–27], similar to wood and low-quality coals. Compared to other bioenergy crops, Miscanthus has a higher energy yield per hectare: 204 GJ ha^{-1} compared to 168 GJ ha^{-1} from poplar and willow short rotation coppice, 27 GJ ha^{-1} from oil seeds bioethanol, and 14–114 GJ ha^{-1} from ethanol produced from starch and sugar [28]. Compared to other agricultural biofuels from wheat, wheat bran, maize and Sorgnum; and woody biofuels from willow and spruce, Miscanthus has shown better performance as a feedstock in small-scale combustion and combined heat and power systems [27,29]. Apart from being used as a biofuel, Miscanthus can be used for the re-cultivation of degraded land [24,30] i.e., for phytostabilization of ash disposals and gravel pit surfaces [11,31,32]. In addition, Miscanthus can be used for the production of cellulose pulp and biodegradable products in industries and as a thermal isolation material [33,34].

So far, the largescale cultivation of Miscanthus has been implemented in several EU countries: in France, 400 ha are covered with Miscanthus [12,35], in Romania more than 600 ha [9,11] in Germany around 3000 ha, in Poland 4000 ha, in the US 6600 ha and in the UK 9000 ha [20,36].

There is no largescale cultivation of Miscanthus in the Republic of Serbia. In 2008, several experimental plots were established on chernozhem and eutric cambisol, providing high yields [16]. According to the last Census of Agriculture (2012), Serbia has plenty of abandoned and unused (set-aside) agricultural land that can be used for bio-crop cultivation without reduction of the existing arable land [37]. Approximately 60,000 ha of unused land covered with chernozem is located in the northern part of the country [38]. In order to initiate cultivation of bioenergy crops in the Republic of Serbia, it is important to investigate the environmental and energy aspects of Miscanthus plantations' cultivation—from land preparation to harvesting, transport and combustion in heating appliances.

An environmental impact analysis can be performed by using the Life Cycle Assessment (LCA) methodology. LCA is a tool that establishes the creation of a mass balance over an investigated system by analyzing all inputs and outputs of a system product over its entire life cycle or over some phases of a life cycle [5] and is widely accepted as one of the best methodologies for the assessment of bioenergy systems [39]. Several LCA studies examining the suitability of Miscanthus for heat or electricity production in the European context have been published so far. However, most of these studies focus only on CO_2 equivalents (eq) emissions released along the entire lifecycle of Miscanthus [12,14,40–43] or are "cradle-to-gate" studies (i.e., investigating impacts occurring from the planting of rhizomes to the bioenergy plant gate, distributor, etc.) [8,10,44]. Other environmental impacts considered are carbon sequestration potential and land use change from cultivation of Miscanthus on agricultural land [45,46] or on grassland [47,48], and emissions of pollutants (carbon monoxide, nitrogen oxides, hydrocarbons and particulate matter) from Miscanthus combustion [9,49].

Authors of this research attempted to model and carry out a more comprehensive "cradle-to-grave" study that will consider CO_2 eq emissions, acidification, eutrophication, ozone depletion, ionizing radiation and toxicity potential, occurring along the entire Miscanthus life cycle. In order to approve or disapprove the environmental suitability of Miscanthus for household heating in Serbia, a comparison with traditionally used heating sources, such as lignite briquettes and wood logs, is done. The novelty of this research is the modeling of the thermal energy final consumer. Free-standing family houses are chosen as the final consumer, since they represent the most common type of residential building in Serbia. This type of building has a specific annual average heating demand per m^2, which is calculated according to the characteristics of the building and heating system used. Using this method, the number of final consumers that can be supplied with thermal energy from the cultivation of Miscanthus on a defined area can be provided. This value can also be a useful parameter when aiming at the replacement of traditionally used fossil fuels with miscanthus briquettes and when assessing other potentially renewable heating sources.

This kind of analysis could also prove to be rather applicable to the whole Balkan region, since no similar analysis has been conducted in this region so far. This can also help promotion of the establishment of Miscanthus plantations in this area.

2. Materials and Methods

2.1. Goal, Scope, System Boundaries and Functional Unit

The aim of this research is to assess the environmental performance of Miscanthus in order to initiate its use as a potential heating source in individual heating systems in the Republic of Serbia. All relevant energy inputs, fuel consumption, and emissions occurring from the cultivation of Miscanthus to the thermal energy production for household heating are considered, using LCA methodology (considered inputs are: water from nature, herbicide application and irrigation, diesel fuel (for agricultural machinery), electricity (for briquetting process, etc.), herbicide (Glyphosate) and fertilizer (NPK 15:15:15) from technosphere, taken from Ecoinvent 3 and Agri-footprint databases. Production of the machinery and other infrastructure facilities is excluded from the analysis. Rhizome cultivation and transportation, together with ash disposal from combustion processes, are also excluded. The functional unit of the system under study is unit area of land (1 ha) used for Miscanthus cultivation, and a reference flow is average dry yield of Miscanthus obtained from III–VII year of cultivation on chernozem experimental field, 23.5 ± 1.02 t (85% d.m.) [16]. Average wet Miscanthus yield obtained on chernozem is around 30 t (66.5% d.m.) [23]. The final product of the system is the amount of heat (GJ) released from the combustion of 23.5 t (85% d.m.) of Miscanthus briquettes in boilers for household heating. Considering boiler efficiency of around 0.85 and lower heating value of Miscanthus of about 18.3 GJ t^{-1} [26,50], the released net heat during the combustion of 23.5 t of Miscanthus is around 360 GJ. This amount of heat is designated as a functional unit for the comparison of Miscanthus briquettes with wood logs and coal. For LCA, SimaPro 8.0.4.7 (PRé Sustainability, The Netherlands) software was used.

2.2. System Description

Miscanthus life cycle has been divided into several operations [23]: (1) Field preparation for planting, (2) Rhizome planting, (3) crop management, (4) harvesting, (5) balling, (6) transport from the field to the briquetting machine, (7) briquetting, (8) transport to the final consumer, and (9) combustion and thermal energy production (Table 1).

Table 1. Miscanthus (*Miscanthus* × *giganteus* Greef et Deu.) life cycle operations, machinery selection, productivity and fuel consumption, calculated based on the functional unit (1 ha) and the reference flow (23.5 t, 85% dry matter (d.m.) Miscanthus).

Operation:	Machinery Used (References Used)	Energy Consumption (MJ ha^{-1})	Productivity (h ha^{-1})	Diesel Consumption (kg ha^{-1})	Pollutant Emissions (kg ha^{-1}) [a]
Herbicide application	Tractor (60 kW) + sprayer, Glyphosate: 3 kg ha^{-1} [51,52] [b]	32	0.20	1.54	HC: 0.0066 CO: 0.0233 NOx: 0.2211 PM: 0.0310 CO_2: 20.5917 CH_4: 0.0017 N_2O: 0.0007
Plowing (20–30 cm)	Tractor (103 kW) + plow [53,54]	217	0.9	27.46	HC: 0.0295 CO: 0.1658 NOx: 0.3123 PM: 0.0181 CO_2: 20.1638 CH_4: 0.0007 N_2O: 0.0009
Disc harrowing	Tractor (>100 kW) + disc harrow 450 cm [54,55]	76	0.34	8.74	HC: 0.0112 CO: 0.0626 NOx: 0.1180 PM: 0.0068 CO_2: 7.6174 CH_4: 0.0003 N_2O: 0.0003
Harrowing	Tractor (>100 kW) + harrow 700 cm [54,55]	60	0.33	9.57	HC: 0.0108 CO: 0.0608 NOx: 0.1145 PM: 0.0066 CO_2: 7.3934 CH_4: 0.0003 N_2O: 0.0003
Rhizomes planting	Tractor (35 kW) + semi-automatic potato planter (4 row) [23,56]	183	3.33	8.42	HC: 0.0669 CO: 0.2634 NOx: 0.2211 PM: 0.0035 CO_2: 2.5500 CH_4: 0.0001 N_2O: 0.0001
Fertilization	Tractor (60 kW) + mineral fertilizer spreader Rauch AXIS, 24 m, NPK: 667 kg 15:15:15 ha^{-1} [52,54,55]	18	0.28	1.21	HC: 0.0092 CO: 0.0326 NOx: 0.0471 PM: 0.0050 CO_2: 3.5700 CH_4: 0.0002 N_2O: 0.0001
Irrigation	Aggregate type "Sever Valmont"—15 kW with diesel engine "TAM" (110.4 kW), Water: 180 m^3 ha^{-1} [57–60]	163	0.41	7.57	HC: 0.0134 CO: 0.0755 NOx: 0.1423 PM: 0.0082 CO_2: 9.1857 CH_4: 0.0003 N_2O: 0.0004

Table 1. *Cont.*

Operation:	**Machinery Used (References Used)**	**Energy Consumption (MJ ha^{-1})**	**Productivity (h ha^{-1})**	**Diesel Consumption (kg ha^{-1})**	**Pollutant Emissions (kg ha^{-1}) ^{a}**
Harvesting	New Holland H8080, 168 kW, 750 HD Specialty Head with 4.7 m cutting width [61–63]	321	0.96	27.46	HC: 0.0887 CO: 0.5159 NOx: 1.0577 PM: 0.0564 CO_2: 59.5324 CH_4: 0.0021 N_2O: 0.0030
Baling and loading	Tractor (26 kW) + Wellger 730press [64]	216	5.22	13.46	HC: 0.1049 CO: 0.4129 NOx: 0.3466 PM: 0.0485 CO_2: 32.2789 CH_4: 0.0026 N_2O: 0.0010
Transport, tractor (t km)	Tractor (60 kW) + 2 trailers Zmaj-470/489 [64]	23.5 × 120 = 2820	6	36.74	HC: 0.1968 CO: 0.6996 NOx: 1.0098 PM: 0.1062 CO_2: 76.5 CH_4: 0.0036 N_2O: 0.0030
Briquetting	BIOMASSER® 2Duo-Set: −Shredder RK7 (7.5 kW) −2x BIOMASSER® Duo BS 207 (12.4 kW) [50]	5922	79	-	Emissions from electricity (Rep. of Serbia) consumption (Ecoinvent process)
Transport, truck (t km)	Truck >20 t	23.5 × 100 = 2350	2	32.25	Agri-footprint process: "Transport, truck >20 t, EURO2, 100%LF, default/GLO Mass"
TOTAL		7208	87	121.27	HC: 0.5380; CO: 2.3125; NOx: 3.4031; PM: 0.2905; CO_2: 239.3833; CH_4: 0.0119; N_2O: 0.0099.
Combustion	biomass boiler, 30 kW power, efficiency 0.85, Miscanthus Lower Heating Value (LHV) = 18.3 GJ t^{-1}	Energy release (MJ ha^{-1}): 365,542	-	-	HC: 0.3411; CO: 942.8898; NOx: 49.3373; PM: 5.2842.
TOTAL		energy output/energy input (EO:EI) = 51:1			HC: 0.8791; CO: 945.2023; NOx: 52.7404; PM: 5.5747; CO_2: 239.3833; CH_4: 0.0119; N_2O: 0.0099.

[a]: data calculated from Swiss Federal Office for the Environment (FOEN) database [65]; [b]: data obtained through Personal communication. HC: hydrocarbons; CO: carbon-monoxide; NOx: nitrogen oxide; PM: particulate matter; CO_2: carbon-dioxide; CH_4: methane; N_2O: dinitrogen monoxide.

Field preparation for planting of Miscanthus rhizomes is considered to be done in autumn and includes the following activities: herbicide application, deep plowing, harrowing, and disc harrowing. Herbicide glyphosate is used for perennial weed control. At the end of autumn, the land is plowed at a depth of 20–30 cm and additionally processed (harrowed and disc harrowed) in the following spring. After a period of frosts, rhizomes are planted at a depth of 5–10 cm, with a planting density of two rhizomes per m^2 (this is the optimal planting density for Miscanthus cultivated in a Belgrade wider area) [66]. Other authors also consider this planting density optimal for Miscanthus [22,67]. Fertilization is done by applying 667 kg of NPK 15:15:15 per ha (100 kg N ha^{-1} + 100 kg P_2O_5 ha^{-1} + 100 kg K_2O ha^{-1}) once per year between harvesting of biomass and plant re-growth in spring [66]. It is assumed that one of the main restrictions for successful growing of Miscanthus in the steppe regions of northern Serbia (with annual precipitation less than 600 mm) is limited water supply [16]. Thus, the irrigation of Miscanthus crops is taken into account. A linear irrigation system is considered as one of the most used systems on Serbian agricultural fields [57,59,60,68]. Miscanthus harvesting is considered to be performed in February when, despite lower yields compared to the autumn harvest, better biomass combustion properties are obtained [16,25,69]. The lowest Miscanthus yield obtained on chernozem from spring harvest is 23 t (66.5% d.m.) for wet yield or 18 t (85% d.m.) for dry yield, while the highest Miscanthus yield obtained is 42 t (66.5% d.m.) for wet yield or 33 t (85% d.m.) for dry yield (data obtained from personal communication).

Field operations occurring only during the first year, such as herbicide application, plowing, harrowing and disc harrowing, are also considered, in order to investigate the environmental impact of the whole Miscanthus life cycle. The small rectangular baling system is considered for balling of Miscanthus, as it is the most commonly used in Serbia [64], due to the small investment power of agricultural enterprises and unfavorable credit terms of other technologies (such as for large round and large rectangular bales) [64]. The average size of a bale obtained with the balling press is 800 mm × 490 mm × 360 mm. The average weight of a single Miscanthus bale is experimentally determined and amounts to 15 kg. The average annual yield of Miscanthus produces 1566 bales. Since the capacity of the most commonly used transportation aggregate on Serbian farms, tractor with two modified trailers, type Zmaj-470/489 (Zmaj, Belgrade-Zemun, Serbia) is around 300 bales, it has to make six rounds (six return loads) for the transport of 1566 bales. This is assumed to take six hours, considering the average distance of 10 km between the field and the briquetting machine and average tractor speed of around 20 km h^{-1}. Before transport and briquetting, Miscanthus bales are left on the field to dry. When the average moisture content drops to approximately 15% [70], 23.5 t of Miscanthus bales are loaded and transported to the briquetting location. The distance between field and the location of the briquetting machine is considered to be 10 km [14,71,72]. Briquetting of Miscanthus bales is considered to be done one the briquetting machine BIOMASSER® 2Duo-Set (SERWIS AKPiA, Poznan, Poland) [50]. Briquettes are further transported by a truck to the final consumer, and utilized for thermal energy production by combustion in a boiler with assumed capacity of 30 kW and efficiency of 0.85. Distance between the briquetting location and a final consumer is assumed to be 100 km [8].

A free-standing family house was chosen as the final consumer, since it represents the most common type of residential building in the Republic of Serbia [73]. The average annual heating energy demand for this type of building is calculated to be 954 MJ per m^2. The calculation considered the participation of the certain subtypes of free-standing family houses and their specific heat consumption, which are reported in the Intelligent Energy Europe Programme (IEE) project "Typology Approach for Building Stock Energy Assessment" (TABULA) [73].

Potential soil carbon (C) sequestration from cultivation of Miscanthus on 1 ha of agricultural land is calculated considering the estimation of above and belowground biomass of Miscanthus (i.e., the mass of senescent leaves, post-harvest residues and rhizomes) and C content of 48.3% in the crop [30,50]. The mass of the aboveground residues is estimated considering the loss of 35% of the Miscanthus yield in spring, when the crop is harvested [23]. The total amount of belowground biomass is estimated at 16% of the total aboveground biomass (harvest + aboveground residue) [46]. From the total C in belowground biomass, 86% is assumed to be lost annually (1% from rhizomes decomposition and 85% from fine root turnover) [74]. From the total carbon entering the soil (from above and belowground biomass) only 18% is considered to contribute to the annual increase of soil organic carbon (SOC), while the rest is considered to be lost as CO_2 during microbial respiration [74]. Both gross soil C sequestration potential and net soil C sequestration potential are calculated [75], together with net CO_2 eq emission reduction. Soil C sequestration potential is also calculated for minimal and maximal Miscanthus yields.

Direct and indirect N_2O emissions from the soil are estimated by using methodology presented by the Intergovernmental Panel on Climate Change (IPCC) [76]. Direct N_2O emissions are defined as emissions of N_2O from managed soils that occur directly from N-fertilizer application and crop residues, and indirect emissions are emissions of N_2O from atmospheric deposition of N volatilized from managed soils [76]. N_2O emissions are converted to CO_2 eq, which together with CO_2 eq emitted along the whole Miscanthus lifecycle, constitute total CO_2 eq emissions.

2.3. Life Cycle Inventory

Life cycle inventory for Miscanthus cultivated on 1 ha is calculated in relation to the reference flow and presented in Table 1.

2.3.1. Inputs: Machinery Used, Fuel Consumption, Productivity

Due to the absence of specific, primary data for Miscanthus cultivation in Serbian agricultural conditions, secondary data were used (data from scientific and technical publications, reports, data obtained in communication with relevant scientific institutions, etc.) [50–62,64,77]. The selection of agricultural machinery is carried out on the basis of an analysis of available data on most commonly used machines for specific agricultural operations in Serbia. According to data from the last Census of Agriculture, 95% of all used tractors in Serbia are older than 15 years [68], thus with lower efficiency. Since the most widely used tractors are those with engine power between 19 and 37 kW (62% from all existing tractors) [68], inputs related to this tractor category have been used whenever possible. Specialized machines are used for irrigation, harvesting and briquetting. Data regarding the harvesting of Miscanthus were taken from other relevant studies [61,63], since such data for Serbia have not been found.

2.3.2. Inputs: Herbicide, Fertilizer, Electricity

A modified process from the Ecoinvent database is used to study the application of herbicides; it takes into consideration the consumption of the electricity produced only from Serbian power grid. The same modifications are applied for the electricity consumed by the briquetting machine. As an input for fertilization operation, the Agri-footprint database process is used. All modifications of database processes used in this analysis are in Section 1 of Supplementary Material (Table S1).

2.3.3. Emissions from Machinery Operation

Regarding emissions from machinery use during Miscanthus field operations, data from the non-road emissions database, compiled by the Swiss Federal Office for the Environment (FOEN) are used [65], due to the absence of national databases of such kind. The amount of released carbon-dioxide (CO_2), carbon-monoxide (CO), methane (CH_4), hydrocarbons (HC), nitrogen oxides (NOx), dinitrogen monoxide (N_2O) and particulate matter (PM) are provided in kg h^{-1} and differs for each year of machinery production. Emissions from each operation are calculated according to the power of the tractor engine used (kW) and the machine productivity (h ha^{-1}) (Table 1). The year 1995 was chosen as a reference for machinery production, since it coincides with the age of agricultural machines used in Serbia. For other operations, such as transports and briquetting, emissions are already quantified in corresponding Ecoinvent and Agri-footprint processes used in this analysis. Since no primary data are available in Serbia for emissions of pollutants during Miscanthus combustion, emission details from a study published by Schmidl et al. have been used [49]. Emissions of CO_2 from briquettes combustion are excluded on the assumption of biomass CO_2 neutrality (the amount of CO_2 released at the end of a plant life cycle equals to the amount of CO_2 assimilated during plant growth) [40,43,78].

2.4. Inventory for Coal and Wood

For the comparison of Miscanthus briquettes with coal and firewood, supply chains of these fuels are also constructed. Both of these fuels are assumed to be extracted in Serbia. Regarding the type of coal, lignite briquettes have been chosen since lignite is the most common type of coal extracted in Serbia and used in IHS (Section 1). For firewood production and combustion and for the heat generation from lignite combustion, Ecoinvent processes are used. Both processes are modified to accurately represent the Serbian case (Table S1). Electricity inputs used for lignite briquettes production and wood logs combustion are modified to fit into Serbian electricity mix, same as for the Miscanthus briquetting operation. Since these fuels are domestically produced, transports by trans-oceanic tankers are excluded. Only transport by lorry is considered for wood logs, and for lignite briquettes, only transport by freight train, lorry and light commercial vehicle. A mixture of hardwood and softwood tree species used for mixed logs production is modified to more accurately resemble Serbian conditions [79]. The production of coal stove and furnace for logs combustion, as well as production of any infrastructure are excluded from the analysis. A lower heating value of lignite briquettes is considered to be 19.5 GJ t^{-1} and lower heating value of wood logs as 18.5 GJ t^{-1} [26]; efficiency of the heating appliances is assumed to be 0.85.

2.5. Impact Assessment Method

The ReCiPE Midpoint (H) method is used for Miscanthus life cycle impact assessment (LCIA). ReCiPE is one of the most recent and most harmonized indicator approach available for life cycle impact assessment. Even though the endpoint impact assessment approach investigates the actual damage at the end of the cause-effect chain, its application requires more knowledge and data for modeling a larger part of the ecosystem and for calculation of synergy and cumulative effects [5,80–82]. The ReCiPE midpoint oriented approach is more comprehensive—it can examine up to 18 impact categories, and is used more often as an indispensable part of scientifically based decision analysis [83–85]. As a result, the midpoint approach is used in this study. From other perspectives in the ReCiPE midpoint approach, "Hierarchist" (H) is used, since it considers most common policy principles, timeframes, and other issues [84].

Fourteen midpoint impact categories were considered in this study: climate change (CC), ozone depletion (OD), terrestrial acidification (TA), fresh water eutrophication (FE), marine eutrophication (ME), human toxicity (HT), photochemical oxidant formation (POF), particulate matter formation (PMF), terrestrial ecotoxicity (TET), freshwater ecotoxicity (FET), marine ecotoxicity (MET), ionising radiation (IR), water depletion (WD) and fossil depletion (FD). The analyzed impact categories and corresponding category indicators and pollutant receiving mediums are shown in Table 2. Other categories concerning land occupation and transformation (agricultural land and urban land occupation and natural land transformation), together with metal depletion, have not been not evaluated, since the infrastructures that impact these categories are out of the scope of this study.

Table 2. Impact categories, units and receiving mediums of emitted pollutants and resources depletion occurring along life cycles of lignite briquettes, wood logs and for both present and future scenario of Miscanthus briquettes production, and emission reduction/increase from the substitution of lignite briquettes and wood logs with Miscanthus briquettes and from the substitution of present scenario with future scenario in [kg] and in [%]:

Impact Category:	**Units and Receiving Mediums:**	**Lignite Briquettes (LB)**	**Wood Logs (WL)**	**Miscanthus Briquettes (MB)**	**Future Scenario (FS)**	**Emissions Reduction:**					
						LB ➡ MB	**%**	**WL ➡ MB**	**%**	**MB ➡ FS**	**%**
Climate change (CC)	kg CO_2 eq [a] (to air)	71,240.30	6032.66	1181.21 [X]	3389.43	−70,059.09	−98.34	−4851.45	−80.42	2208.21	65.15%
Ozone depletion (OD)	kg CFC_{-11} [b] eq (to air)	0.00066	0.00069	0.00091	0.00061	+0.00025	+27.30	+0.00022	+24.40	−0.00029	−32.81
Terrestrial acidification (TA)	kg SO_2 eq (to air)	246.63	60.90	38.43	36.18	−208.2	−84.42	−22.47	−36.90	−2.25	−5.86
Fresh water eutrophication (FE)	kg P eq (to freshwater)	175.89	4.07	1.49	1.37	−174.4	−99.15	−2.58	−63.31	−0.13	−8.51
Marine eutrophication (ME)	kg N eq (to freshwater)	69.06	37.15	3.33	3.10	−65.73	−95.18	−33.82	−91.04	−0.23	−6.89
Human toxicity (HT), Terrestrial ecotoxicity (TET), Freshwater ecotoxicity (FET), Marine ecotoxicity (ME)	kg 1,4-DB [c] eq (to urban air, urban soil, freshwater, marine water)	116,557.53	4620.55	1154.85	1061.93	−115,402.68	−99.01	−3465.70	-75.01	−92.88	−8.04
Photochemical oxidant formation (POF)	kg NMVOC [d] (to air)	259.25	130.33	100.96	97.32	−158.28	−61.06	−29.37	−22.54	−3.64	−3.61
Particulate matter formation (PMF)	kg PM10 eq (to air)	120.19	47.87	20.06	19.25	−100.13	−83.31	−27.81	−58.09	−0.81	−4.03
Ionising radiation (IR)	kBq [e] U235 [f] eq (to air)	1714.33	443.39	74.48	24.06	−1639.84	−95.66	−368.91	−83.20	−50.42	−67.69
Water depletion (WD)	Water m^3	−123,981.75	−14,842.10	−5640.42	−5680.60	+118,341.33	+95.45	+9201.68	+62.00	−40.18	0.71
Fossil depletion (FD)	kg oil eq	181,28.19	1664.98	393.93	295.06	−17,734.25	−97.83	−1271.05	−76.34	−98.87	−25.10

[a] eq: equivalents, [b] CFC_{-11}: Chlorofluorocarbon; [c] 1,4-DCB: 1,4 dichlorobenzene; [d] NMVOC: Non Methane Volatile Organic Carbon compound; [e] kBq: kilobecquerel; [f] U235: uranium isotope; MB: Miscanthus briquettes, present scenario; FS: Miscanthus briquettes, future scenario; emissions reduction is marked with "−" sign; emissions increase is marked with "+" sign. [X]: see Table 3.

3. Results and Discussion

3.1. LCIA of Miscanthus Briquettes

LCIA results for the whole Miscanthus briquettes supply chain are depicted in Figure 1.

From all operations, "briquetting" exhibits the highest environmental impact. In impact categories FE, FET, MET, HT and WD, briquetting has almost 100% impact due to highest emissions of 1,4 DB eq, compared to all other operations, i.e., 1130.8 kg compared to a total of 1154.9 kg. In categories such as CC, TET, ME, FE, FET, MET, HT and FD, high impacts result from the utilization of lignite for electricity generation, since more than 50% of all electricity used in Serbian electrical grid is produced from lignite combustion in thermal power plants. High impact in FET, MET, HT and FD arise from the process of "treatment of spoil from lignite mining". In the IR impact category, the highest contribution comes from "Tailing from Uranium milling", since one part of imported electricity from Romania, Bulgaria and Hungary is produced in nuclear power plants. The briquetting operation exhibits lowest impacts in OD and POF categories—around 2%—due to low emissions of CFC_{-11} eq and Non Methane Volatile Organic Carbon compound (NMVOC). Such a high negative impact on the environment from the briquetting process is due to the high amount of electricity consumption of the machine (mainly produced from fossil fuels) and lower productivity compared to other operations (around 80 h is needed for briquetting of total of 23.5 t d.m. of Miscanthus, Table 1). This operation shows a positive impact—103.16%, only in the category of Water Depletion, since almost 19% of the total electricity used in Serbia is produced in run-of-the-river hydro power plants, which do not require substantial water storage [86]. According to Goedkoop and De Schryver, the water use scenario, in which water is released very close to the place of consumption, is considered not to produce any water shortage [84]. This kind of situation is marked with a minus sign ($-$), since no negative impact in the impact category is recorded.

The second most environmentally influencing operation from the Miscanthus life cycle is "combustion". This operation expresses impacts in only four out of fourteen categories (in POF, PMF, TA and ME). In the POF category, "combustion" dominates with an impact of around 92%, since 92% of the total amount of HC released though the whole life cycle of Miscanthus is emitted during combustion of Miscanthus briquettes. Due to the high emissions of particulate matter emissions compared to other processes (16 kg from total of 20 kg of PM10 eq emitted), impact from combustion in the PMF category is also 92%. The high impacts in TA and ME categories—71% and 58%, respectively—are due to high NOx eq emissions during Miscanthus combustion, which is in correlation with N content of the Miscanthus [49]. In impact category CC, the result is 0%, since biomass combustion is considered to be CO_2 neutral (Section 2.3.3).

The third-most burdensome operation from the Miscanthus life cycle is "transport by truck". In category Ozone Depletion, this operation exerts the highest impact—around 22%—due to emissions of around 0.000198 kg CFC_{-11} eq from a total of 0.000911 kg of CFC_{-11} eq. The same impact of around 22% is manifested in TET, due to proportionally high emissions of 1,4 DB eq. In impact categories CC and FD, impacts are around 12%, due to relatively high CO_2 eq emissions (around 146.3 kg from total of 1181.21 kg CO_2 eq) and relatively high diesel consumption, compared to other processes (32.25 kg ha^{-1}, Table 1). Even with a higher fuel consumption (36.47 kg ha^{-1}) and lower productivity than "Transport by truck" (6 h ha^{-1}) (Table 1), "Transport by tractor and trailers" exerts a similar, but slightly lower impact. The reason for this lies in a less-detailed inventory. As mentioned before, the inventory of the "Transport by truck" process was taken from the "Agri-footprint" database and inventory of the "Transport by tractor and trailers" process was collected by analyzing available data from the literature, which considered a less number of potential pollutant emissions.

For better transparency, the impacts of Miscanthus field operations are depicted separately in Figure 2.

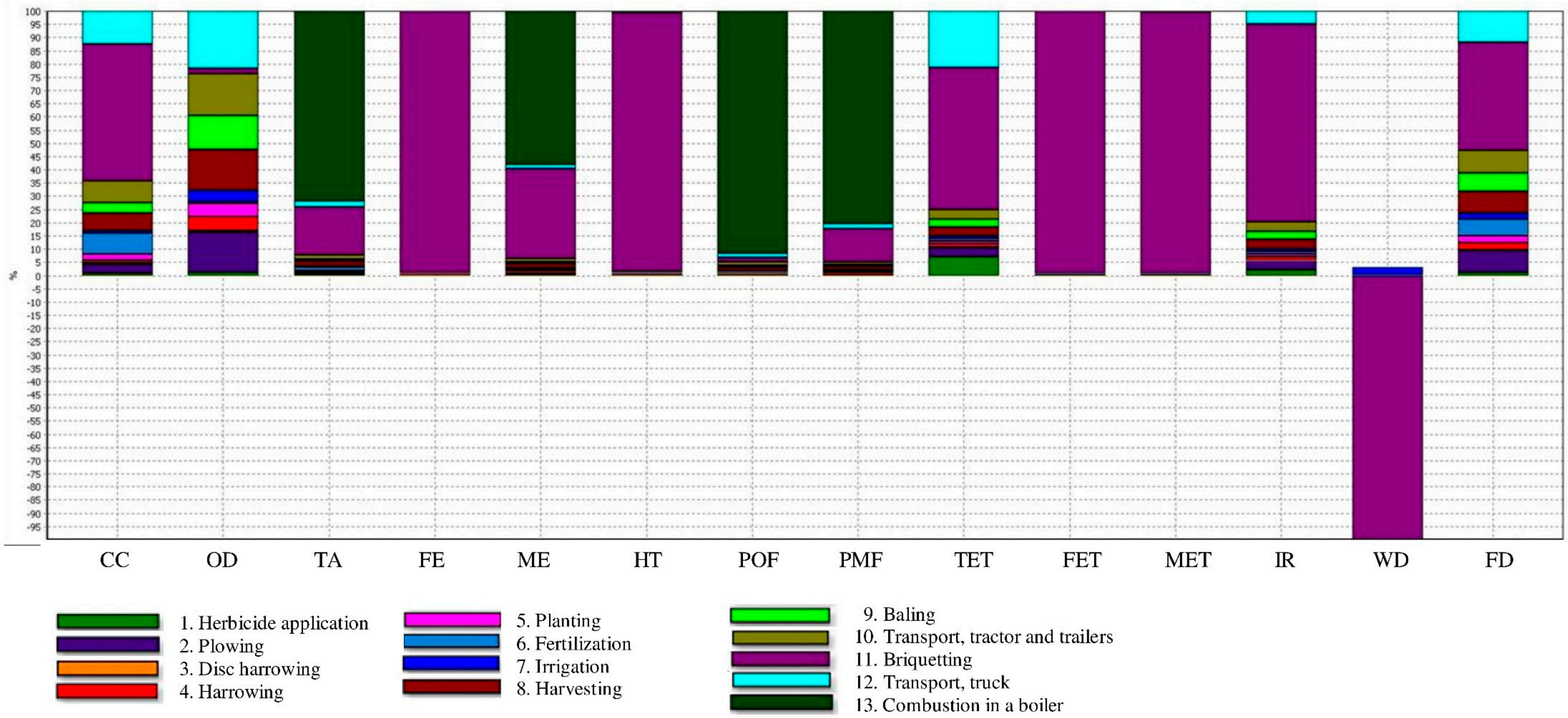


Figure 1. LCIA for Miscanthus briquettes.

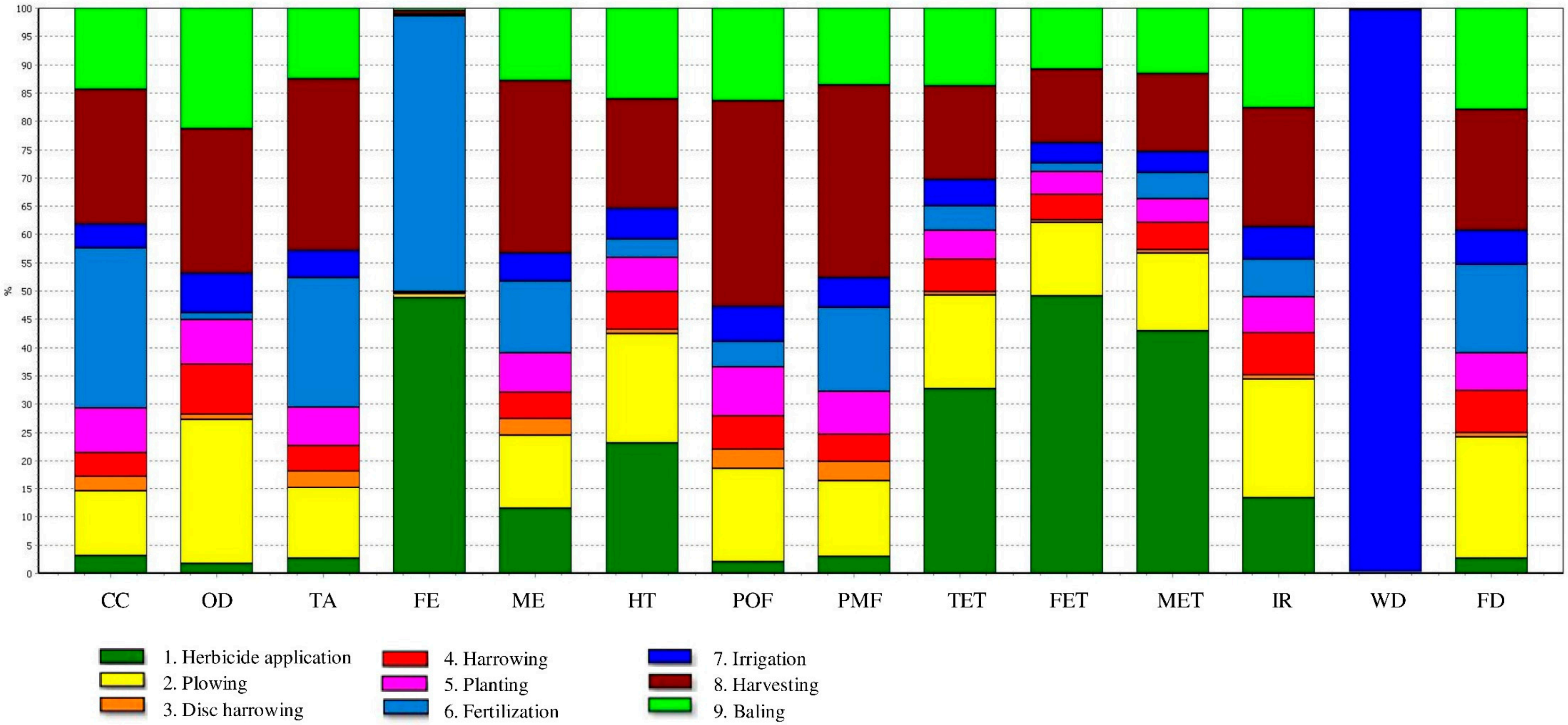


Figure 2. LCIA for Miscanthus field operations.

Compared to other field operations, “Harvesting” and “Plowing” had the highest energy and diesel consumption, and were more time consuming (Table 1). Even though they had the same impact on most categories (such as OD, TE and FD) and same diesel consumption per ha, “Harvesting” had a higher impact in CC, TA, ME, POF and PMF categories due to different emission factors, which are in correlation with different tractor engine powers used. According to the FOEN database emissions from diesel combustion are slightly higher for more powerful engines. While “Plowing” is performed by a tractor of 103 kW engine power, “Harvesting” is done by a mower-conditioner of 168 kW engine power (Table 1). Both of these two operations have the highest influence—around 15%—on the OD category, right after “Transport by truck” and “Transport by tractor”, due to a higher level of diesel consumption.

A field operation ‘hotspot’ process is “Herbicide application”, which exerts the highest impact on several categories: FE, HT, FET, TET and MET—49%, 23%, 49%, 33% and 43%, respectively, due to glyphosate production and use. “Fertilization” also exerts a high impact—around 49% in the FE category, 28% in the CC category, 23% in the TA category and 16% in the FD category—due to NPK fertilizer production and diesel consumption. Impact from “Balling” varies from 13% to 17% in all categories, mainly due to diesel consumption. In category WD, the only process that exerts an impact is “Irrigation”. Irrigation, Disc harrowing, Harrowing and Planting exert much-lower impacts in all studied categories since they are not highly fuel and time consuming. In general, a higher operational time, a higher consumption of fossil fuel, and powerful diesel engines increase the impact of the Miscanthus life cycle operation.

3.2. Comparison of Miscanthus with Lignite and Wood Logs

Results of the comparative LCIA for Miscanthus briquettes (MB), wood logs (WL) and lignite briquettes (LB) are depicted in Figure 3.

For the same net heat produced, lignite briquettes exhibit the highest impact in all categories (100%), due to the highest consumption of lignite and electricity along the life cycle, as compared to other fuels. As opposed to LB, MB exhibits the lowest impacts in all categories. The only exception is the OD category, where LB expresses the lowest impact (around 73%) and MB exhibits the highest (100%) as a consequence of diesel fuel combustion in agricultural machinery. The category in which no negative impacts from all three types of fuels are observed is Water Depletion, due to the consumption of a significant amount of electricity produced from run-of-the-river hydro power plants (Section 3.1). Emission reduction by the substitution of LB and WL by MB are summarized in Table 2. The substitution of 22 t of lignite with 23.5 t of Miscanthus briquettes would lead to a reduction of 70,059 kg CO_2 eq, 208 kg SO_2 eq, 174 kg P eq, 66 kg N eq, 115,403 kg 1,4-DB eq, 158 kg NMVOC, 100 kg PM10 eq, 1,640 kBq U235 eq and oil eq of 17,734 kg. Even with no negative impact on water reserves, water savings by using Miscanthus briquettes would be less for 118,341 m^3 compared to lignite briquettes. Emissions of CFC_{-11} eq would be 0.00025 kg higher. Similar results for CO_2 emissions reduction were obtained by Lewandowski et al., where the combustion of Miscanthus instead of hard coal saves 90% of CO_2 emissions [40].

The substitution of 23 t of wood logs with 23.5 t of Miscanthus briquettes would lead to the following emissions savings: 4852 kg of CO_2 eq, 23 kg of SO_2 eq, 3 kg of P eq, 34 kg of N eq, 3466 kg of 1,4-DB eq, 29 kg of NMVOC, 28 kg of PM10 eq, 369 of kBq U235 eq, and 1271 kg of oil eq. Water savings would be 9202 m^3 less and emissions of CFC_{-11} eq would be 0.00022 kg higher

The results of the comparative analysis with lignite and wood show a better performance by Miscanthus in 12 of the 14 investigated impact categories and thus designate it as a more environment-friendly option for household heating.

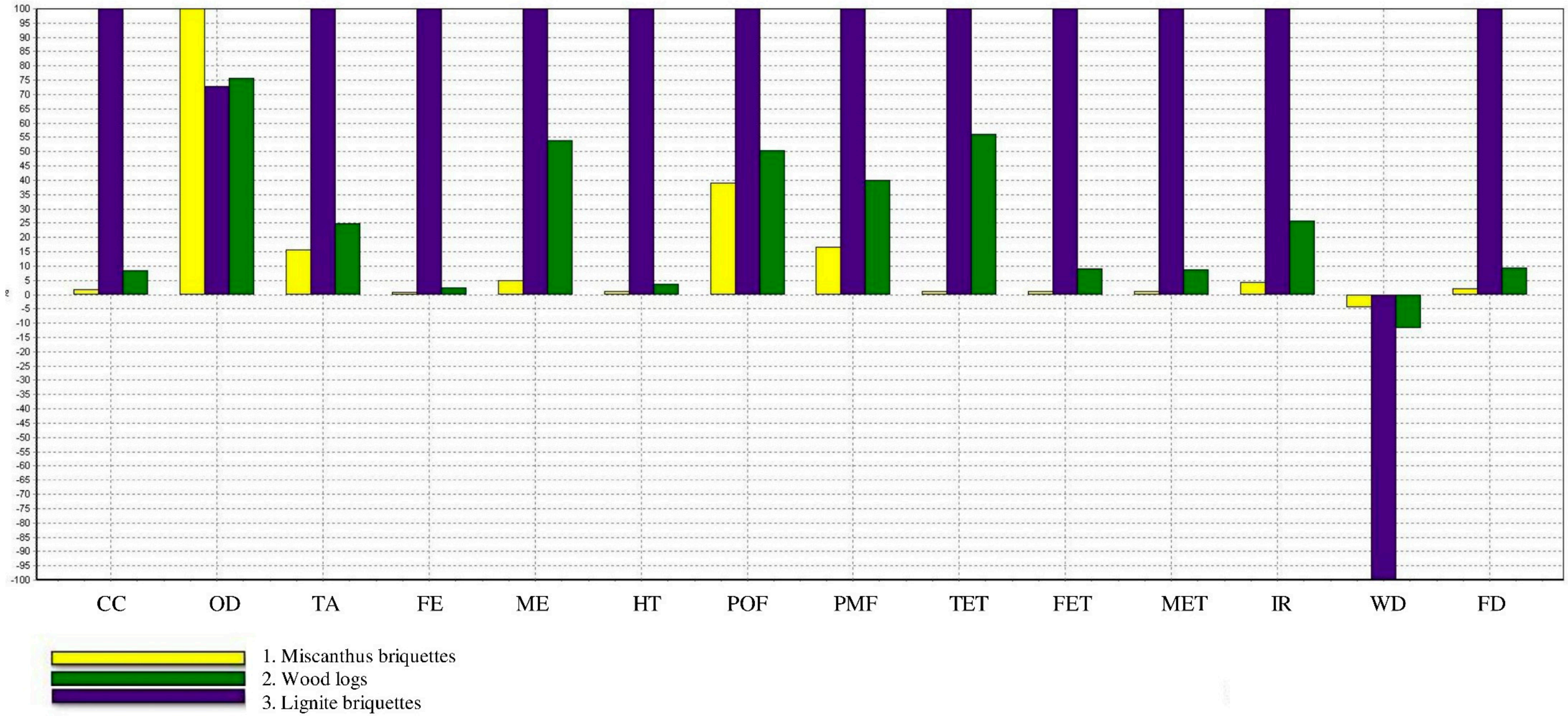


Figure 3. Comparative LCIA for Miscanthus briquettes, wood logs and lignite briquettes.

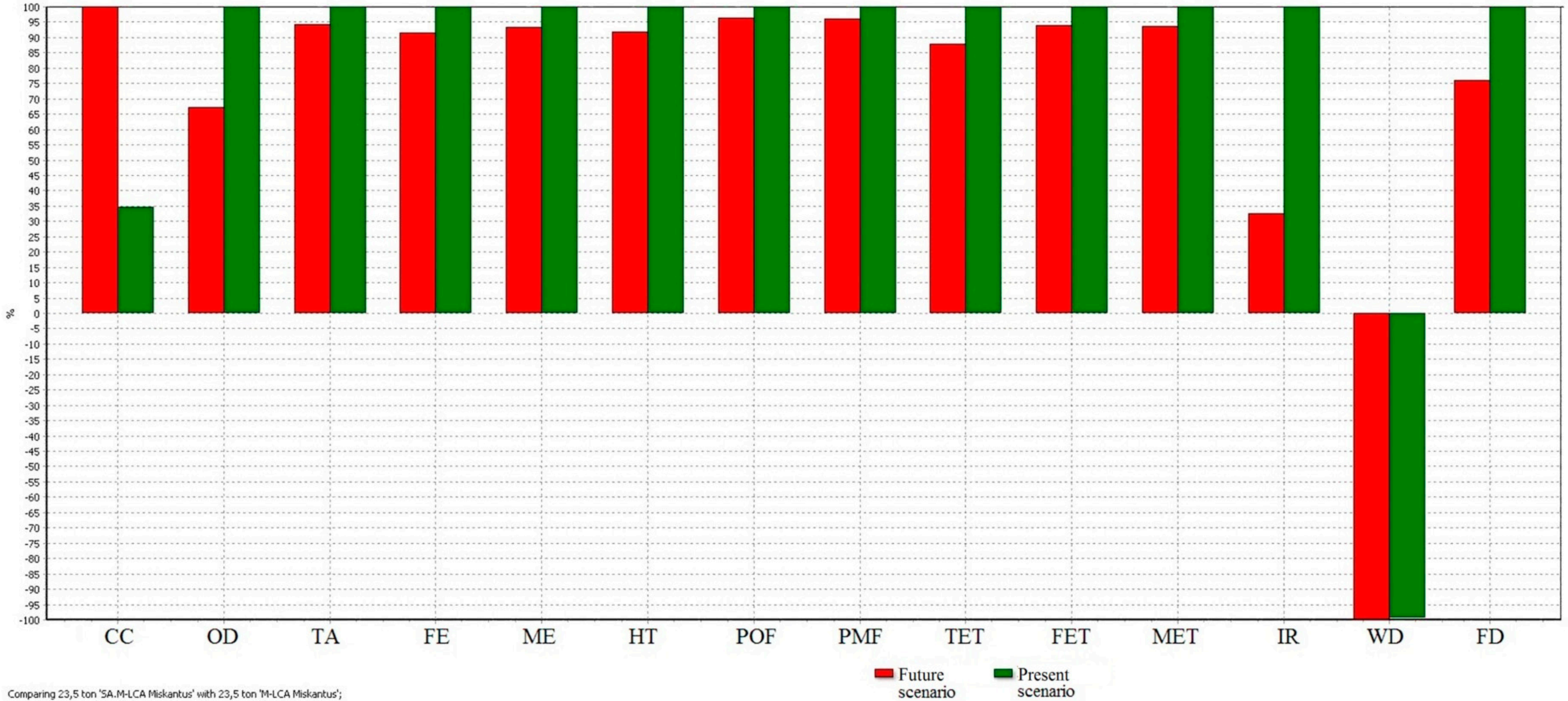
3.3. Sensitivity Analysis

Considering the inevitable modernization of agricultural machinery and in Serbia, together with the construction of more energy-efficient buildings in the near future, a sensitivity analysis was performed and future scenario evaluated. This scenario takes into account: (1) the use of more modern and efficient agricultural machinery (produced in 2020), (2) the use of tractor engine power 75–130 kW for all agricultural operations, (3) fuel consumption to be 20% less, (4) productivity to be 20% higher, (5) 20% of electricity used for briquetting machine is obtained from renewable energy sources (from geothermal, wind and wood chips co-generation plants; see Section 1, Supplementary Material) instead of imports, (6) a 50% higher productivity in the transportation process from the field to the briquetting location (due to consideration of 50% higher load capacity of trailers), (7) transportation distance between briquetting location and final user to be 50 km instead of 100 km, and (8) average annual heating energy demand of around 266.4 MJ m^{-2} due to an increased number of energy efficient houses (by application of better thermal insulation and more efficient heating systems [48]. Since 2020 is taken as the year of machinery production, predicted emission factors for this year are taken from the FOEN database and recalculated for the aforementioned case. The comparison of these two scenarios is depicted in Figure 4.

In almost every impact category, the future scenario expresses only slightly lower impacts, except in IR, where the impact is almost 68% lower, and CC, where the impact is 65% higher (Table 3). According to the FOEN database, the EU5 standard used for 2020 machines considers much higher CO_2 eq emission factors (kg h^{-1}) compared to 1995 machines, but lower emissions of other pollutants (NOx, N_2O, methane, hydrocarbons and particulate matter) [65]. Decreased impact in the IR category is due to the exclusion of electricity obtained from import, i.e., from nuclear power plants. Impacts in the CC category from both scenarios are separately discussed and depicted in Figure 5.

The inclusion of 20% RES in the production of electricity consumed by briquetting machines lowers the impact of briquetting operation by 12%. On the other hand, the use of more powerful tractor engines increases CO_2 eq emissions for all field operations. The increase is especially high for operations where very low-power engine tractors were replaced, such as for planting and balling in which the impact on climate change increased 25 and 22 times, respectively. The increasing load capacity of trailers proportionally lowered the impact from transport of bales from the field, and shortening the transportation distance of Miscanthus briquettes proportionally lowered the impact from transport by truck.

It may be concluded that the utilization of power optimized agricultural machinery as well as the increased participation of RES in all energy-consuming stages of the process would significantly reduce the environmental impact of Miscanthus life cycle operations.



Comparing 23,5 ton 'SA.M-LCA Miskantus' with 23,5 ton 'M-LCA Miskantus';
Method: ReCiPe Midpoint (H) V1.11 / Europe Recipe H / Characterization

Figure 4. Comparative LCIA for the present scenario and future scenario of Miscanthus briquettes.

Table 3. Direct and indirect N_2O emissions and carbon sequestration potential from Miscanthus cultivation calculated for minimal, average and maximal Miscanthus yield (detailed calculation is given in Section 2 of Supplementary Material).

		Residual Biomass		N Content		N Content	N_2O-N_{dir}	N_2O_{dir}	N_2O_{total}	CO_2 eq Y	Total C input from Biomass into Soil			Gross Soil C		Gross CO_2 eq	CO_2 eq (Total)	Net CO_2 eq	Net Soil C
		(t)		(kg)		(kg)	(kg)	(kg)	(kg)	(t)	(t C ha^{-1} $Year^{-1}$)					(t CO_2 eq ha^{-1} $Year^{-1}$)			(t C ha^{-1} $Year^{-1}$)
Yield (85% dry Matter) t $Year^{-1}$		**a**	**b**	**a**	**b**	**a + b**	**a + b**	**a + b**	**a + b**	**a + b**	**a**	**b**	**b 86%**	**a + b**	**a + b 18%**	**Total**	$X^{\#} + Y$		
min:	18	8	4.16	80	20.8	100.8	2.01	3.16	3.24	0.96	3.86	2.00	1.72	5.58	1.00	3.68	2.16	1.52	0.41
average:	23.5	10.92	5.5	109.2	27.5	136.7	2.37	3.72	3.80	1.13	5.27	2.66	2.29	7.56	1.36	4.99	2.33	2.66	0.72
max:	33	15.36	7.74	153.6	38.7	192.3	2.92	4.59	4.67	1.39	7.42	3.74	3.22	10.64	1.91	7.02	2.59	4.43	1.21

a: aboveground residual biomass; b: belowground biomass; a + b: aboveground + belowground biomass; N_2O-N_{dir}: direct N_2O emissions; N_2O_{dir}: conversion of N_2O-N emissions to N_2O according to IPCC (Intergovernmental Panel on Climate Change) formulae; *indirect* N_2O emissions: emissions of atmospheric deposition of N volatilized from managed soils calculated according to IPCC formulae; N_2O *total* = *direct* + *indirect* N_2O emissions; CO_2 eq (Y): emissions of N_2O calculated as CO_2 eq (considered GWP of N_2O is 298 times higher than of CO_2); CO_2 eq total emissions: sum of CO_2 eq (from N_2O) (Y) and CO_2 eq emitted during whole annual Miscanthus life cycle (X); $^{\#}$ for ^{X} see Table 2. Gross CO_2 eq emissions reductions: Gross soil C sequestration potential calculated as CO_2; Net CO_2 eq emissions reduction = Gross CO_2 eq − CO_2 eq total.

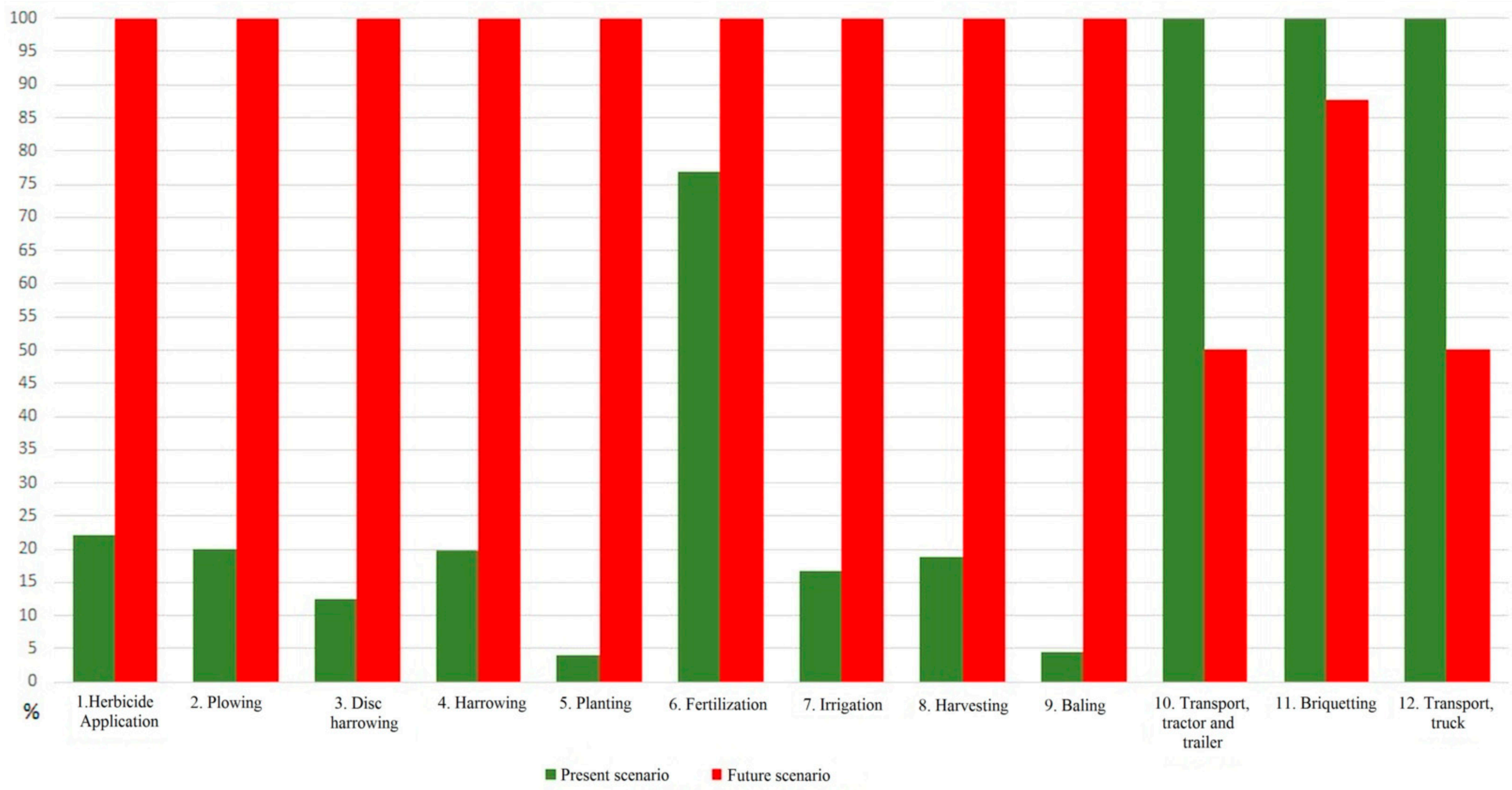


Figure 5. Comparison of climate change impacts from present and future scenarios of Miscanthus briquettes.

3.4. SOC and Land Use Change

3.4.1. Present Scenario

Considering the reference flow of 1 ha, potential gross soil C sequestration from both aboveground and belowground residues in the present scenario can vary from 1 to 1.91 t C ha^{-1} $year^{-1}$, depending on Miscanthus yield (Table 3). For average Miscanthus yield of 23.5 t d.m. ha^{-1} $year^{-1}$, 1.36 t C ha^{-1} can be sequestered annually (Tables 1 and 3). Borzecka-Walker et al. obtained slightly lower values of gross soil sequestration potential, from 0.47 to 1.18 t C ha^{-1} $year^{-1}$, from 16.2 t ha^{-1} d.m of annual Miscanthus yield cultivated on heavy black earth type of soil [87]. Matthews and Grogan, and Clifton-Brown et al., obtained sequestration rates at levels up to 0.93 t $year^{-1}$ [74,88].

Total N_2O emissions from Miscanthus cultivation can vary from 3.24 to 4.67 kg ha^{-1} $year^{-1}$, where direct emissions account from 3.16 to 4.59 kg ha^{-1} $year^{-1}$, and indirect emissions are approximately 0.08 kg ha^{-1} $year^{-1}$ (Table 3). Total CO_2 eq emitted vary from 2.16 to 2.59 t ha^{-1} $year^{-1}$. CO_2 eq emissions per MJ of released heat for average Miscanthus yield are 0.006 kg. This coincides with results obtained by Smeets et al., and Parajuli et al., who obtained 0.004 kg to 0.005 kg CO_2 eq MJ^{-1} [8,14]. The total annual emissions of CO_2 eq per m^2 of a heated free-standing family house is 3.04 kg CO_2 eq m^{-2}.

Net soil C sequestration potential varies from 0.41 to 1.21 t C ha^{-1} $year^{-1}$. For average Miscanthus yield, net soil C sequestration potential is 0.72 t C ha^{-1} $year^{-1}$ (Table 3). Potential soil carbon sequestration rate for perennial crops published by other authors is around 0.62 t C ha^{-1} $year^{-1}$ [75,89,90]. Considering C sequestration potential of set-aside land of around 0.38 t C ha^{-1} $year^{-1}$ [75,89,90], C sequestration from Miscanthus replacing the set-aside land can vary from 0.03 t C ha^{-1} $year^{-1}$ to 0.81 t C ha^{-1} $year^{-1}$. When average Miscanthus yield is obtained, 0.34 t C ha^{-1} can be sequestered annually (Table 4). If the net soil C sequestration potential is converted to CO_2 eq, the cultivation of Miscanthus on chernozem soil can save from 1.52 to 4.43 t CO_2 eq ha^{-1} annually (Table 4). Considering cultivation of Miscanthus on 20,000 ha of unused, set-aside land, from 0.6 kt to 16.6 kt C can be sequestrated annually.

Table 4. Net carbon sequestration potential of Miscanthus briquettes for both present and future scenarios and the amount of carbon saved or lost by the replacement of set-aside land with Miscanthus crops.

Miscanthus Yield	**Net C Sequestration Potential for MB**	**Net C Sequestration Potential for FS**	**MB: Replacement of Set-Aside**	**FS: Replacement of Set-Aside**
(t ha^{-1} $Year^{-1}$, 85% Dry Matter)	**(t C ha^{-1} $year^{-1}$)**			
18	1.52	−0.68	0.03	−0.57
23.5	2.66	0.46	0.34	−0.26
33	4.43	2.23	0.83	0.23

MB: Miscanthus briquettes, present scenario. FS: Miscanthus briquettes, future scenario. Replacement of set-aside = Net soil C sequestration potential − 0.38 t C ha^{-1} $year^{-1}$. 0.38t C $ha^{-1}year^{-1}$ is C sequestration potential of set-aside land [75,89,90].

3.4.2. Future Scenario

Due to higher CO_2 eq emissions in the future scenario (Table 2), calculations of net C sequestration potential from Miscanthus cultivation was found to be lower than the present scenario (Table 4). For average Miscanthus yield, CO_2 eq emissions per MJ of released heat is 0.012 kg, which is higher compared to the present scenario. However, the total annual emissions of CO_2 eq per m^2 of a heated free-standing family house was calculated to be 2.44 kg CO_2 eq m^{-2}, which is lower than in the present scenario. This is calculated on the basis of an increase in energy efficiency of heated buildings in the near future.

Net carbon sequestration is only possible when average and maximal Miscanthus yields are obtained—0.12 t C ha^{-1} year^{-1} and 0.61 t C ha^{-1} year^{-1}, respectively. In a scenario where minimal Miscanthus yield is obtained, there will be no net C sequestration; 0.19 t C ha^{-1} will be lost annually. The replacement of set-aside land with Miscanthus crops in a future scenario will cause C losses for both minimal and average Miscanthus yields obtained—0.57 t C ha^{-1} year^{-1} and 0.26 t C ha^{-1} year^{-1}, respectively. For maximal Miscanthus yield, C sequestration will be 0.23 t C ha^{-1} year^{-1} (Table 4). In this regard, the annual C losses from 20,000 ha can vary from −11.3 kt to −5.1 kt for minimal and average Miscanthus yields. For maximal Miscanthus yield, 4.55 kt C can be sequestrated annually. Even though the future scenario shows higher CO_2 eq emissions than the present, it still exhibits a 95% lower impact in the CC category compared to lignite briquettes and a 44% lower impact compared to wood logs (Table 2).

3.5. Energy Ratio

Energy input for the entire life cycle of Miscanthus briquettes is around 7.2 GJ and energy input for only field operations is around 1.2 GJ (Table 1). Lewandowski and Schmidt reported slightly higher energy input values for field operation (considering soil cultivation, crop management, irrigation and harvest)—around 2 GJ [7]. In a case where land preparation and rhizomes planting operations are omitted, the energy input is around 6.57 GJ. The net heat amount released from combustion of 23.5 t of Miscanthus briquettes in a boiler is 365.5 GJ, and obtained energy output:input ratio (EO:EI) is very high—around 51:1. A similar output:input ratio for Miscanthus was obtained for western Germany, 47.3:1 [43] and 54:1 [7]. The equivalent amount of net heat can be produced by burning 22 t of lignite briquettes or 23 t of wood logs in stoves or furnaces (Section 2.4). With this amount of heat, around 383 m^2 of a free-standing family house can be heated annually, if the present scenario is considered or 1372 m^2 for the future scenario.

4. Summary and Conclusions

This study scrutinizes Miscanthus (*Miscanthus giganteus*) as a potential sustainable energy source for individual household heating systems in the Republic of Serbia. Based on data obtained from a five-year cultivation of Miscanthus on chernozem soil and data regarding energy and fuel consumption, pollutant emissions and productivity of agricultural machinery, a potential Miscanthus supply chain was constructed and LCA conducted.

It is concluded that the substitution of lignite by Miscanthus briquettes in model-households would lead to a reduction in CO_2 eq emissions by 98%, SO_2 eq by 84%, P eq by 99%, N eq by 95%, 1,4-DB eq by 99%, NMVOC by 61%, PM10 eq 83%, U235 eq by 96% and oil eq by 98%; save 95% less water, and emit 27% more CFC_{-11}. The substitution of wood logs by Miscanthus briquettes would save 20% of CO_2 eq, 63% of SO_2 eq, 37% of P eq, 91% of N eq, 75% of 1,4-DB eq, 23% of HC, 58% of PM10 eq, 63% of U235 eq, 76% of oil eq and 62% less water, and emit 24% more CFC_{-11} eq. These results designate Miscanthus as a more environmental friendly option for household heating, compared to the traditionally used coal and wood.

The LCIA results imply that the Miscanthus supply chain “hotspot” operation is briquetting, due to its low productivity and high electricity consumption. Considering only field operations, most burdensome operations are “Herbicide application” and “Fertilization”, due to herbicide and fertilizer production and fuel combustion in agricultural machines. In general, most burdensome activities in the Miscanthus life cycle are pollutant emissions mainly caused by diesel fuel combustion in outdated agricultural machinery and a high share of fossil fuels used for electricity production. Both of these impacts will decrease over the next few years due to the devised and ongoing increase of RES in Serbian electricity production, as well as the renewal and better efficiency of agricultural machinery. The increased participation of RES resulted in a 12% lower impact in the Climate Change category for a future scenario briquetting operation, compared to the same operation in a present scenario.

The utilization of a modern, more-powerful, machinery showed beneficial results in all investigated impact categories, except in Climate Change, where a 65% higher impact was predicted by FOEN database.

In the present scenario, net C sequestration is possible when both high and low Miscanthus yields are obtained; however, in a future scenario, net C sequestration is attainable only when maximal Miscanthus yield is obtained. Thus, the replacement of 20,000 ha of set-aside land with Miscanthus crops by using the present agricultural practice in the Republic of Serbia would lead to SOC increase from 0.6 kt C to 16.6 kt C and by using advanced mechanization, annual C losses would vary between −11.3 kt C and −5.1 kt C, except for maximal Miscanthus yield obtained, where annual SOC increase would be 4.55 kt C. This increased impact caused by higher emission factors of CO_2 can be reduced by using optimized machinery in terms of size/power for each Miscanthus life cycle operation. Nevertheless, both present and future scenarios of Miscanthus briquettes' utilization in individual household heating systems turned out to be unequivocally more sustainable options compared to the currently used fossil fuels' scenarios. Therefore, further development of *Miscanthus giganteus* bioenergy plantations in the Republic of Serbia is strongly recommended.

Nevertheless, certain aspects of the cultivation of Miscanthus for energy purposes should be discussed. Even though the cultivation of Miscanthus on chernozem and other types of high-quality soils results in high yields, the influence of cultivation on other types of low-quality soils should also be considered. Climate change also has a huge impact on potential Miscanthus yields. Extreme weather patterns were recorded across Europe over the last couple of years—extremely warm and dry summers or extremely humid and rainy seasons. This can result in a high fluctuation of annual Miscanthus yield, which is also important when discussing economic revenue with potential Miscanthus cultivators. Since the production of briquettes from agricultural biomass is still costlier compared to the traditionally used fuels for household heating, the state could stimulate the establishments of plantations by offering subsidies to farmers and by providing financial help to household owners in a bid to make inevitable changes in heating systems' installations for better efficiency of combustion of Miscanthus briquettes. On the other hand, the cultivation of Miscanthus can be initiated not only for energy purposes but also for phytoremediation of heavily polluted soils, and as a resource for constructing of building materials and making of biodegradable industrial products.

Supplementary Materials: The following are available online at http://www.mdpi.com/1999-4907/9/10/654/s1, Table S1: Modified Ecoinvent and Agri-footprint processes used in LCA of Miscanthus, wood logs, lignite briquettes and sensitivity analysis (future scenario), Section 1. Modified Ecoinventand and Agri-footprint processes used in LCA of Miscanthus, wood logs, lignite briquettes and sensitivity analysis (future scenario), Section 2. Soil Organic Carbon.

Author Contributions: M.P., M.K. and B.B. conceived and designed the analysis. M.P. conducted LCA in SimaPro software. M.P. and D.A. modeled the heat demand for the final consumer. Ž.D. delivered data from miscanthus cultivation in Serbia. M.P., M.K., D.A. and B.B. discussed the results and implications. M.P., M.K., D.A., B.B. and Ž.D. wrote the manuscript.

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