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Life Cycle Assessment Of Biomass Chains: Wood Pellet From Short Rotation Coppice Using Data Measured On A Real Plant

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► **To cite this version:**

Cinzia Buratti, Francesco Fantozzi. Life Cycle Assessment Of Biomass Chains: Wood Pellet From Short Rotation Coppice Using Data Measured On A Real Plant. *Biomass and Bioenergy*, 2010, 34 (12), pp.1796. 10.1016/j.biombioe.2010.07.011 . hal-00748066

HAL Id: hal-00748066

<https://hal.science/hal-00748066>

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Manuscript Number: JBB-D-09-00289R1

Title: LIFE CYCLE ASSESSMENT OF BIOMASS CHAINS: WOOD PELLET FROM SHORT ROTATION COPPICE USING DATA MEASURED ON A REAL PLANT

Article Type: Research Paper

Keywords: Life Cycle Assessment;
EcoIndicator 99;
Environmental impact;
wood pellet;
Short Rotation Coppice;
pellet plant energy consumptions measurements;
Energy Return Ratio (ERR).

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Order of Authors: Francesco Fantozzi, Professor; Cinzia Buratti, Professor

Abstract: This paper presents a LCA study about household heat from Short Rotation Coppice wood pellets combustion. The overall process, from field growth to ash disposal, was considered; environmental analysis was carried out using a LCA software programme (Simapro 7.0) and adopting the EcoIndicator 99 model for the evaluation of the global burden; analysis with EPS 2000 and EDIP methodologies were also carried out in order to compare the different approaches. For the pellet production process, mass and energy flows were measured on an existing Italian plant, while other data were obtained from the Literature; a comparison between results obtained using only data from Literature and using data from the existing plant was made, showing for the pelleting phase a value of about 23% lower if measured data are used. The LCA study showed that agricultural operations account for most of the environmental impact if evaluated both with EcoIndicator 99 and EPS 2000; EDIP gave results that were not very reliable for this chain, due to the high weight given to the infrastructures and machinery construction. The comparison between data obtained considering and not considering the infrastructures contribution in the LCA analysis with EcoIndicator 99 showed a modest contribution of infrastructures on the final score (about 2%). The overall impact evaluated with EcoIndicator 99 is considerably less than the one caused by natural gas heating. The Energy Return Ratio was finally calculated; a value of 3.25 was found, good if compared to the one for the methane combustion, equal to 6.

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Deleted.

5. Figure 3 has to work in grey scale not colour for the print edition, please check if it is alright, if not redraw.
Redraw.

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All data were expressed in μP .

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Dear Sirs,

enclosed please find the revised version of the paper ***LCA ANALYSIS OF BIOMASS CHAINS. PART II: WOOD PELLET FROM SHORT ROTATION COPPICE USING DATA MEASURED ON A REAL PLANT*** by ***C. Buratti and F. Fantozzi***; as suggested by the Reviewers, the title was modified in ***LIFE CYCLE ASSESSMENT OF BIOMASS CHAINS: WOOD PELLET FROM SHORT ROTATION COPPICE USING DATA MEASURED ON A REAL PLANT***.

The manuscript has not been previously published, is not currently submitted for review to any other journal, and will not be submitted elsewhere before a decision is made by this journal.

Thank you very much for your attention

With my best regards

Cinzia Buratti

Perugia, March 15 2010

***Detailed Response to Reviewers**

| Comments of the Reviewers and answers | |
|--|---|
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*Responses to Technical Check Results

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| The SI units is not correct (please use the SI system and superscripts appropriately). There is no SI unit for year (it is not constant), JBB uses the abbreviation "y" | Corrected in all the paper. |
| References to web sites need to have the last date of access of the web site. | Added. |
| The instructions to authors are very clear on how the references should be laid out. | All the References were corrected. |

1 **LIFE CYCLE ASSESSMENT OF BIOMASS CHAINS: WOOD PELLET FROM SHORT**
2 **ROTATION COPPICE USING DATA MEASURED ON A REAL PLANT**

3
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10 **Abstract:** This paper presents a LCA study about household heat from Short Rotation Coppice wood
11 pellets combustion. The overall process, from field growth to ash disposal, was considered; environmental
12 analysis was carried out using a LCA software programme (Simapro 7.0) and adopting the EcoIndicator 99
13 model for the evaluation of the global burden; analysis with EPS 2000 and EDIP methodologies were also
14 carried out in order to compare the different approaches. For the pellet production process, mass and
15 energy flows were measured on an existing Italian plant, while other data were obtained from the
16 Literature; a comparison between results obtained using only data from Literature and using data from the
17 existing plant was made, showing for the pelleting phase a value of about 23% lower if measured data are
18 used. The LCA study showed that agricultural operations account for most of the environmental impact if
19 evaluated both with EcoIndicator 99 and EPS 2000; EDIP gave results that were not very reliable for this
20 chain, due to the high weight given to the infrastructures and machinery construction. The comparison
21 between data obtained considering and not considering the infrastructures contribution in the LCA analysis
22 with EcoIndicator 99 showed a modest contribution of infrastructures on the final score (about 2%). The
23 overall impact evaluated with EcoIndicator 99 is considerably less than the one caused by natural gas
24 heating. The Energy Return Ratio was finally calculated; a value of 3.25 was found, good if compared to
25 the one for the methane combustion, equal to 6.

26
27 **Key-words:** Life Cycle Assessment; EcoIndicator 99; Environmental impact; wood pellet; Short Rotation
28 Coppice; pellet plant energy consumptions measurements; Energy Return Ratio (ERR).

29

30 **1. INTRODUCTION**

31 The European Community undertook an ambitious program aimed at improving the
32 sustainability of energy use across Europe. The European Union (EU) and its Member States
33 encourage the use of renewable sources of energy and the improving of energy efficiency; in
34 this context, the European Commission released a proposal for a Directive on the promotion of
35 the use of renewable energy [1]. It addresses all sectors of the renewable energy industries,
36 helping them to reach the Commission's target for 20% of Europe's energy produced by
37 renewable sources by 2020.

38 Biomass is equally suited for electricity generation, heating, cooling and fuels for transport,
39 offering environmental benefits, but it can also present environmental pressures. In fact a
40 substantial increase in the use of biomass from agriculture, forestry and waste for producing

1 energy could put additional pressure on farmland and forest biodiversity, as well as on soil and
2 water resources. Encouraging the development of renewable energy from biomass might also
3 counteract other environmental policies and objectives, such as waste minimization or
4 environmentally oriented farming. Moreover, it is likely that a fraction of the biomass consumed
5 in the EU, necessary to satisfy the above-mentioned target, will be imported because of lower
6 production costs in third countries. This could entail a risk of even greater pressures on natural
7 ecosystems and could lead to uncultivated land being brought into cultivation, including land
8 with a high level of stored carbon or otherwise representing high environmental value. It is
9 evident that the huge utilization of biomass as energy resource needs an appropriate
10 management as a key action to optimize the use of resource and to reduce the environmental
11 impact associated.

12 The Life Cycle Assessment (LCA) methodology could be employed to evaluate the
13 environmental and energetic sustainability of biomass energy chains, and in particular their
14 greenhouse gas savings. In fact LCA method proved to be a valuable tool for documenting and
15 analysing environmental considerations of product and service systems, that need to be part of
16 decision-making process towards sustainability.

17 In this paper thermal energy generation from wood pellet combustion, obtained from dedicated
18 energy crops (poplar), was analyzed and compared to natural gas chain used in a domestic
19 boiler. Ecological and energetic balances were performed, using the life cycle perspective, by
20 means of the EcoIndicator 99 model (adopting the hierarchical version) [2] and the Cumulative
21 Energy Demand (CED) method [3] and calculating the Energy Return Ratio (ERR). Further
22 analysis with EPS 2000 and EDIP methodologies were carried out, in order to compare the
23 different approaches.

24 Wood pellet is a product which is gaining popularity around the world as biofuel, while in Italy it
25 is still in the take off phase, requiring also specific set of rules to classify the product and its
26 quality. Pellet can be obtained from different feedstocks, such as residual biomass from
27 agricultural or industrial processes, forestry pruning and dedicated crops; they are gaining
28 interest because of the poor availability of sawdust from forestry residuals, but wood pellet from
29 energy crops may require more energy in the overall process from wood to pellet, than the
30 quantity obtained from the combustion of the biofuel.

1 Therefore it seemed necessary to carry out the LCA of wood pellet from Short Rotation Coppice
2 (SRC), namely poplar, to provide an objective procedure to evaluate the energetic and
3 environmental expenses. The resulting pellet is not high quality, in compliance to CTI – R04/5
4 recommendation [4], because it is characterized by an ash content of 1,5% – 2,5%, being the
5 raw material composed by wood chips with an important percentage of bark.

6 Mass and energy flows of the overall process were evaluated including SRC cultivation,
7 pelletising, WP combustion, ash disposal and all required transportation.

8 There are several studies on the environmental impact assessment of wood pellet chains [5, 6].
9 However in all cases biomass used for the pellet production is represented by raw materials as,
10 for example, residues from the wood lumber processing or sawdust and chips from wood
11 processing industries. For the pellet production step, these studies employ data from Norwegian
12 or Canadian companies; in this study one of the most important Italian pellet plant was
13 monitored during the production phase, in order to measure the energy required in each phase
14 of the process. The major difficulty of this study, in fact, was to find data about the pelletising
15 process, because only a few data about the various phases of the process were available in the
16 Literature [7, 8, 9]. In addition a comparison between renewable and fossil chains through a
17 single ecological index that includes not only the greenhouse gas balance but also other
18 important environmental impacts was carried out. Finally, unlike the cited LCAs studies, in the
19 present paper the impact of machinery and infrastructures used in the pellet chain and their
20 incidence on the global burden was also considered.

21 The Energy Return Ratio (ERR) was then calculated, in order to compare the pellet chain to
22 other conventional energy sources such as natural gas.

24 **2. METHODOLOGY AND INPUT DATA**

25 The aim of the analysis is to assess the environmental impact, on a life cycle horizon, of wood
26 pellet utilisation for thermal energy production. The reference functional unit for the inventory
27 analysis and impact assessment is the thermal energy generation of 1 MJ. All the energy and
28 mass flows in the inventory are normalized to the functional unit.

29 Fig. 1 shows the general system boundaries for the scenario considered in this study. In
30 particular, it includes: wood chips production from SRC, transportation to the pelleting plant,
31 transformation into pellet, transportation of pellets to the final user and combustion in a small

1 domestic boiler (22 kW), including the disposal of ashes. Energy crops production was
2 considered for a plantation with the following features:

- 3 – density: 10.000 cuttings ha⁻¹;
- 4 – cultivation period: 8 y;
- 5 – felling frequency: 2 y.

6 In particular, the agricultural operations considered during the eight years of the cultivation cycle
7 are shown in Tab. 1 [10].

8

9 **Inventory analysis**

10 *Cultivation*

11 Poplar cultivation process considered a biomass production ratio equal to 20 t ha⁻¹ y⁻¹ (dry
12 basis), with a cultivation cycle of eight years. For this reason the process was considered for a
13 standard year, in which each agricultural operation was counted a number of times equal to the
14 average value in the eight years.

15 For each process the following quantities were considered, assuming data from Literature: the
16 amount of machinery needed for a specific operation (operating machines and driving
17 machines), fuel consumption for agricultural machines, amount of fertilizer and pesticide used,
18 atmospheric emissions produced by diesel engines, heavy-metal emissions from tyre abrasion
19 [11], NH₃, N₂O and NO_x air emissions from the application of fertilizers, phosphates water
20 emissions from the application of fertilizers [12], VOC air emissions from the application of
21 pesticides and soil pollution coming from the pesticides residue in the soil [13]. Type of
22 machinery, fuel consumption, materials used and working times are listed in Tab. 2. Cuttings
23 are not taken into account because part of the harvested material is used for the next plantation.

24 *Transportation and storage*

25 The second phase is represented by the transportation of wood chips to the pelleting plant,
26 assuming an average distance of 80 km, with a 28 t lorry, and characterized by a load factor
27 (defined as the mass proportion of actual transported load and maximum load capacity of a
28 vehicle, including the empty return trip) equal to 47%. The atmospheric, soil and water
29 emissions (due to tyre abrasion) and fuel consumptions were calculated according to [14], which
30 also considers the construction phase of the vehicle.

1 The next process is the storage of raw material at the pelletising plant: it was assumed that the
2 movement of raw materials, inside the storage area, is carried out by a skid-steer loader (155
3 kW, load capacity of 5 m³). Fuel consumption was calculated using data privately referred and
4 considering a load/discharge cycle of raw material with the following characteristics:

- 5 – covered distance (there and back): 300 m;
- 6 – average velocity: 10 km h⁻¹;
- 7 – average time for load or discharge: 10 s.

8 Inventory data for the production of this machinery were not available and for this reason it was
9 considered a skid-steer loader with 110 kW power [15].

10 *Pelleting*

11 A few data regarding wood biomass transformation into pellet were available in the Literature [7,
12 8, 9], especially when referred to the single processes. Therefore an Italian pelleting plant was
13 contacted to evaluate mass and energy flows of the various steps, in order to comply the lack of
14 data. The plant is characterized by a production capacity of 2 t h⁻¹. In Table 3 the various
15 sections of the plant are described and the relative measured consumptions are reported:

- 16 – pre-treatment of raw material;
- 17 – drying (the heat source considered is a natural gas boiler which supplies 1000 kWh_{th} per
18 tonne of evaporated water, dispersed into the atmosphere);
- 19 – comminution (provided by two milling sections that grind raw material fine);
- 20 – pelleting (two pellet mills, powered by diesel engines; each of them has a conditioning unit,
21 used to supply corn starch);
- 22 – cooling (pellets reach 70-80°C and after pressing are cooled to 20°C in a counterflow cooler);
- 23 – silage.

24 Electricity consumption of machinery was evaluated directly through an acquisition data system
25 (Multiver 3SN Dossena), which carried out an energy measurement from analogic inputs,
26 through amperometric pliers, for electric current, and, directly, for voltage.

27 Each operation was monitored for a variable period of time, according to the actual loading of
28 the machine. Energy was then referred to the processed quantity.

29 The contribution of the construction of the plant main structures was eventually taken into
30 account, considering only main materials and discarding energy consumptions for assembly.

31 Table 4 shows the infrastructures considered, the materials and their lifetimes.

1 The impact of land occupation due to pelleting plant was considered for an occupied area of 1
2 ha. In particular, it was considered an occupation (8 years) of land for forestry cultivation
3 ($0,0437 \text{ m}^2 \text{ y}^{-1} \text{ MJ}^{-1}$) and a transformation of land from unknown utilization to forestry cultivation
4 ($0,00546 \text{ m}^2$).

5 *Transportation to the user*

6 Pellets, stored in silo, are distributed in bulk by trucks (gross weight 40 t, load factor 46%,
7 distance 80 km), which unload the biofuel by blowing the pellets into the storage room of the
8 user. Mass and energy flows were determined such as in *Transportation and storage*.

9 *Combustion*

10 For the pellet combustion process, a 22 kW pellet boiler was considered, and mass and energy
11 flows were calculated for the manufacturing of the boiler, the pipes for heat distribution inside
12 the building, the heat accumulator, the storage silo and the pellet extraction system. Also in this
13 case the energy necessary for the assembling of the items considered was not taken into
14 account.

15 Tab. 5 shows the assumptions and the total amount of materials considered in this process,
16 together with the emissions into the atmosphere produced by pellet combustion [16, 17].

17 The electricity power due to water circulation pump and the screw pellet extractor was assumed
18 of 230 W, that corresponds to a consumption of $0,0027 \text{ kWh MJ}^{-1}$.

19 *Ash disposal*

20 The last process considered is the disposal of ashes, assuming an ash content of 2%, which
21 corresponds to 1,05 mg of ashes per functional unit. Ashes were considered co-products, that
22 can be used as potassium fertilizer, which can be directly spread on agricultural areas.

23 The method used to attribute environmental burdens to the co-product was the displacement
24 method, in which to the primary product is assigned the total environmental burden, minus
25 credits due to the environmental burdens avoided as a result of co-product displacement of
26 alternative products elsewhere.

27 Dismantling and recycling of machinery and infrastructures were not considered throughout the
28 study.

29 **Impact Assessment**

30 The Impact Assessment was evaluated considering three methodologies: EcoIndicator 99, EPS
31 2000 and EDIP.

1 EcoIndicator 99 is a *damage-oriented* approach, based on the weight given to damages by the
2 different Impact Categories. The uncertainty of EcoIndicator 99 is represented by the three
3 different versions in considering the potential damage due to a particular substance (the
4 *individualist* perspective has a short-term horizon and scarce interest in low-probability impacts,
5 the *hierarchic* one balances short and long-term horizons and has a consensus-based approach
6 to risk, the *egalitarian* one has a long-term horizon and relies heavily on the precautionary
7 principle).

8 EPS 2000 evaluates impacts in order to obtain a parameter based on WTP (*Willingness To*
9 *Pay*), giving an economic value to the damage. It includes the characterization and weighting
10 phases, but no normalization and in particular it examines the effects of pollutants on Human
11 Health.

12 EDIP finally has a mid-point approach, which applies weighting factors on the basis of the
13 environmental targets fixed by the Danish Government or by the International Protocols.
14 Normalization is obtained by dividing the characterization values (referred to the world for the
15 global damages and to Denmark for the local ones) for the per person damage related to the
16 category and to year 1990; the evaluation is made by multiplying the normalized damage for the
17 ratio between the damage per person related to the category and to 1990 and the ones
18 established for the year 2000.

19 20 **3. RESULTS AND DISCUSSION**

21 LCA analysis were carried out considering the following scenarios:

- 22 a) data from pelleting plant, analysis with EcoIndicator 99, EPS 2000 and EDIP;
- 23 b) LCA analysis with EcoIndicator 99 with data from pelleting plant and from Literature;
- 24 c) LCA analysis with EcoIndicator 99 considering and not considering machinery and
25 infrastructures contribution in the final score;
- 26 d) LCA analysis with EcoIndicator 99 for heating from the SRF pellet chain and from natural
27 gas combustion.

28 Results are shown in the following.

29 **a) Comparison between EcoIndicator 99, EPS 2000 and EDIP**

30 *EcoIndicator 99*

1 Table 6 shows the global eco-score (3,19 mPt) and the eco-scores for each damage category.
2 It can be noted that the environmental impact on Human Health is much more important than
3 the impact on Ecosystem Quality and Resources. Moreover, the more relevant impact is the one
4 related to Respiratory Inorganics and Fossil Fuels (Tab. 7) due, respectively, to: particulate and
5 nitrogen oxides emissions from pellet boiler and pellet presses; diesel consumption, in tractors
6 and pellet presses; natural gas consumption in the boiler and for nitrogen fertilizers production.
7 The contribution of pellet combustion to the Fossil Fuels category is negative, because ashes
8 were considered as avoided product and therefore the environmental impact of chemical
9 potassium fertilizer production is subtracted from the global burden associated with the wood
10 pellet.

11 With reference to the distribution of the eco-score among the different macro-processes, it can
12 be observed that the environmental impact is mainly due to biomass cultivation (47% of the total
13 impact) and wood pelleting (26,6%). In particular, among agricultural processes (Fig. 2), the
14 impact deriving from land use is very remarkable (25%), while among the other processes the
15 main contributions are surface dressing (37,5% of the energy crops production impact) and field
16 dressing (20,8%), because of fossil fuels consumption for fertilizer production and nitrogen
17 oxides emissions due to the urea application. When considering the transformation of wood into
18 pellet, the most important contribution is pelleting (61,2% of the overall impact), mainly due to
19 diesel and corn starch consumption.

20 *EPS 2000*

21 The single score value of EPS 2000 was 26,4 mPt (Tab.8), due especially to the damage
22 category *Abiotic Resources* and to the related Impact category *Resources Depletion* (15,6 mPt).
23 This is especially due to the poplar cultivation and to the pellet combustion, because of the high
24 weight given to the metals used in the machinery production (nickel). A high score (8,76 mPt) is
25 also related to *Life Expectancy* due to the pellet combustion, and in particular to the high weight
26 of the atmospheric emission of polycyclic aromatic compounds. If considering the macro-
27 processes, the higher contributions to the single score are due to pellet combustion (44,5%) and
28 to poplar cultivation (30,3%), especially for minerals and metals in the fertilizers production.
29 Furthermore, if machinery and infrastructures are excluded from the evaluation of the single
30 score, a value of 15,7 mPt is obtained (-40,5%).

31

1 *EDIP*

2 Results obtained by EDIP (Tab. 9) are not very reliable, due to the high weight given to the
3 machinery and the infrastructures construction; values of 2,31 mPt and 0,41 mPt were found,
4 because of the high weight given to the atmospheric emissions of iron in the steel production
5 cycle. Therefore the most important Impact Category is *Soil Human Toxicity* (87,1%), while the
6 macro-processes with the higher environmental impact are the transformation of chips into
7 pellet (35,9%) and the pellet combustion (39,3%).

8 **b) Comparison of analysis with data from existing plant and from Literature**

9 The environmental global impacts of the pelleting process obtained through data measured at
10 the Italian pellet plant and through data reported in [5] were both evaluated with EcoIndicator 99
11 and compared. Densification process described in [5] consists of three unit operations: drying,
12 size reduction and pelleting; in the first step, wet sawdust is dried in a rotary drier, using natural
13 gas as fuel. In this process the inputs are electricity, natural gas and diesel, while the outputs
14 are air pollutants (like CO₂, CO, NO_x, SO_x, CH₄ and VOC). Results showed that the single score
15 for the process with data from the pelleting plant was 0,85 mPt while, assuming data reported in
16 [5], it was obtained a value of 1,05 mPt. The environmental burden of the Literature process
17 was mostly due to the natural gas consumption and the category Fossil Fuels represents about
18 83% of the overall impact. On the other hand, the value of the real pelleting process was
19 principally due to the Respiratory Inorganics (43%, caused by nitrogen oxides and particulate
20 emissions) and Fossil Fuels (29,5%) categories.

21 **c) Influence of infra-structures contribution to the final score**

22 The environmental burden of the chain, excluding the impact due to machinery and
23 infrastructures used in all processes, was also evaluated with EcoIndicator 99. It was obtained a
24 value of the single score equal to 3,13 mPt (3,19 mPt was the value obtained considering
25 machinery and infrastructures), showing that their incidence on the global impact was about 2%,
26 mainly caused by machinery employed in the pelleting process.

27 **d) Comparison with the heating from natural gas chain**

28 The comparison with the environmental impact of heat obtained from natural gas combustion
29 was carried out assuming the following processes referring to EcoInvent library [18]:

30 – extraction and production of gas onshore and offshore from Germany, Algeria, Netherlands
31 and Russia;

- 1 – transportation to Italy through pipelines;
- 2 – distribution to consumers through local pipe networks;
- 3 – combustion in a boiler (<100 kW).

4 Results from EcoIndicator 99 show that heat produced from natural gas has a higher impact
5 (6,74 mPt) than heat produced from wood pellet (3,19 mPt), mainly because of fossil resources
6 depletion (Fig. 3).

7 The single score for the methane chain with EPS 2000 is 37,5 mPt, especially due to the Impact
8 Category *Resources Depletion*; it is about 30% higher than the bio-energy chain.

9 The comparison with the methane chain carried out with EDIP showed for the bio-energy chain
10 a single score higher than for the fossil one (2,31 mPt vs. 0,87 mPt).

11 A comparison was finally carried out considering the energy efficiency, in terms of Energy
12 Return Ratio (ERR), defined as the ratio of total usable energy produced from the process
13 analyzed to total energy consumed in operating the process itself.

14 Results show that ERR index was equal to 6 for natural gas chain, while the value for biomass
15 chain was 3,25, in any case higher than the break even point (equal to 1). The main processes
16 which contribute to energy consumption are poplar cultivation (42,1% of the total energy
17 requested) and wood pelleting (37,9%).

18

19 **4. CONCLUSIONS**

20 The environmental impact assessments of a bioenergy chain through LCA methodology and
21 adopting EcoIndicator 99 method for the Life Cycle Impact Assessment step was carried out.
22 EcoIndicator 99 is in fact a well-documented and regularly applied impact assessment method.
23 Nevertheless a calculation with EPS 2000 and EDIP was also carried out, in order to consider
24 the different approaches.

25 The LCA study showed that agricultural operations account for most of the environmental
26 impact, when evaluated with both EcoIndicator 99 and EPS 2000, even if for EcoIndicator 99 a
27 higher Impact is related to *Human Health* while for EPS 2000 it is related to *Resources*
28 *Consumption*; EDIP gave not very reliable results for this chain, due to the high weight given to
29 the infra-structure and machinery construction.

30 For the pellet production process, mass and energy flows were measured on an existing Italian
31 pelleting plant, while other data were obtained from the Literature; a comparison between

1 results obtained using only data from the Literature and using data from the existing plant was
2 made, showing a lower value of the score related to the pelleting phase if calculated with data
3 measured on an Italian plant (- 23%).
4 A further comparison was made between data obtained with EcoIndicator 99 with and without
5 considering the contribution of machinery and infrastructures in the LCA analysis; results
6 showed a modest contribution of infrastructures on the final score (about 2%).
7 A final comparison to heat produced from natural gas shows a 53% lower impact for wood
8 pellets with EcoIndicator 99, a 30% lower impact with EPS 2000 and a 62% higher value with
9 EDIP. Comparisons between the two chains were also conducted in terms of energy efficiency,
10 calculating the ERR index. An important result was obtained, because the biomass chain is
11 characterized by a value of 3,25, while for the natural gas chain ERR is equal to 6. Therefore
12 the biomass chain has a favourable energy balance, because its ERR index is clearly above of
13 breakpoint, equal to 1.

14

15 **NOMENCLATURE**

| | | |
|----|-------|---------------------------------------|
| 16 | ERR | Energy Return Ratio |
| 17 | LCA | Life Cycle Assessment |
| 18 | mPt | milliPoint |
| 19 | NMVOG | Non-Methane Volatile Organic Compound |
| 20 | PAH | Polycyclic Aromatic Hydrocarbons |
| 21 | SRC | Short Rotation Coppice |
| 22 | TOC | Total Organic Carbon |
| 23 | VOC | Volatile Organic Compounds |
| 24 | μPt | microPoint |

25

26 **ACKNOWLEDGMENTS**

27 Authors wish to thank Eng. Marco Barbanera, PhD for his contribution in the calculation activity.

28

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11

12 **Figure 1:** Thermal energy production from wood pellet combustion, data referred to the
13 functional unit (1 MJ).

14 **Figure 2:** Contributions of the agricultural operations to the environmental impact of the energy
15 crops production (EcoIndicator 99).

16 **Figure 3:** Comparison between environmental impact of heat production from wood pellet and
17 natural gas (values in μPt) (EcoIndicator 99).

Table 2: Data summary for the agricultural operations in poplar cultivation.

| Agricultural operations | Machinery | Fuel (kg ha⁻¹) | Materials (kg ha⁻¹) | Time (h ha⁻¹) |
|--------------------------------|--------------------------------------|--------------------------------------|--|-------------------------------------|
| ploughing | tractor (80 kW) + 2-furrow plough | 41,550 | - | 2,340 |
| harrowing | tractor (80 kW) + spring tine harrow | 41,200 | - | 0,790 |
| surface dressing | tractor (51 kW) + fertiliser spread | 1,790 | NPK fertilizer (8-24-24): 500 | 0,160 |
| field dressing | tractor (51 kW) + fertiliser spread | 5,030 | urea: 218 | 0,450 |
| cuttings planting | tractor (51 kW) + two-row planter | 67,280 | - | 6,050 |
| pre-emergency herbicide | tractor (51 kW) + field sprayer | 1,790 | Metolachlor: 1,7; Linuron: 0,5; Pendimethalin: 0,8 | 0,160 |
| post-emergency herbicide | tractor (51 kW) + field sprayer | 13,530 | Pyridate: 1,1 Fluazifop-p-butyl: 0,6 | 1,210 |
| cultivating | tractor (51 kW) + rotary harrow | 7,810 | - | 0,700 |
| harvesting | tractor (130 kW) + SRF harvester | 109,150 | - | 1,590 |
| tree levelling | tractor (80 kW) + spring tine harrow | 240,400 | - | 13,36 |

Table 3: Characteristics of the examined pellet plant and measured electricity consumptions (data referred to the functional unit).

| Sections | Installed Power (kW) | Electricity consumption (Wh kg⁻¹ of pellet) | Materials/Energy |
|----------------------|-----------------------------|---|--|
| Pre-treatment | 10,27 | 1,87 | |
| loading tank | 5,5 | 1 | |
| vibrating screen | 2,2 | 0,4 | |
| magn. separator | 0,37 | 0,07 | |
| cup elevator | 2,2 | 0,4 | |
| Drying | 100,9 | 18,76 | |
| feeding tank | 7,5 | 1,4 | natural gas: 0,72 Wh kg ⁻¹ of pellet |
| rotary drum | 10 | 1,86 | |
| exhaust fan | 75 | 14 | |
| star valve | 2,2 | 0,4 | |
| cup elevator | 2,2 | 0,4 | |
| screw conveyor | 4 | 0,7 | |
| Comminution | 202 | 37,71 | |
| 2 screw extract. | 3,6 | 0,67 | |
| 2 feed screws | 4,4 | 0,82 | |
| 2 hammermills | 150 | 28 | |
| 2 volum. pumps | 44 | 8,22 | |
| Pelletisation | 16 | 2,99 | |
| 2 feed hoppers | 4,4 | 0,82 | diesel: 9,9 g kg ⁻¹ of pellet corn starch: 10 g kg ⁻¹ of pellet |
| 2 conditioners | 8 | 1,5 | |
| 2 presses | - | - | |
| 2 screw conveyor | 3,6 | 0,67 | |
| Cooling | 4,8 | 0,9 | |
| screw extractor | 1,8 | 0,34 | |
| cooler | 3 | 0,56 | |
| Silage | 2,95 | 0,6 | |
| vibrating screen | 0,75 | 0,15 | |
| cup elevator | 2,2 | 0,45 | |

Table 4: Characteristics and lifetimes of the pellet plant infrastructures, considered in the LCA analysis.

| Sections | Infrastructures type | Materials | Lifetime (y) |
|-----------------------|----------------------------------|--|---------------------|
| Pre-treatments | vibrating screen | aluminium: 107,5 kg steel low-alloyed: 107,5 kg | 50 |
| | cup elevator, magnetic separator | steel low-alloyed: 700 kg | 50 |
| Drying | rotary drum | aluminium wrought alloyed: 640 kg aluminium sheet rolling: 640 kg | 10 |
| | exhaust fan | aluminium: 1000 kg steel low-alloyed: 1000 kg | 50 |
| | natural gas boiler | refractory: 70 kg cast iron: 4200 kg chromium steel: 230 kg steel low-alloyed: 190 kg rock wool: 40 kg | 20 |
| | cup elevator, screw conveyor | steel low-alloyed: 700 kg | 50 |
| Comminution | 2 hammermills | reinforced steel: 2500 kg steel sheet rolling: 2500 kg | 10 |
| | 2 feed screws, 2 screw extractor | Steel low-alloyed: 700 kg | 50 |
| Pelleting | 2 presses | steel low-alloyed: 4000 kg sheet rolling: 4000 kg | 10 |
| | 2 feed hoppers, 2 screw conveyor | steel low-alloyed: 700 kg | 50 |
| Cooling | cooler | steel low-alloyed: 200 kg | 15 |
| | screw extractor | steel low-alloyed: 210 kg | 50 |
| Silage | vibrating screen | aluminium: 107,5 kg steel low-alloyed: 107,5 kg | 50 |
| | silo (100 m ³) | glass fibre: 3800 kg cast iron: 500 kg reinforcing steel: 500 kg | 25 |
| | cup elevator | steel low-alloyed: 350 kg | 50 |

Table 5: Input data for pellet combustion phase [16, 17].

| Materials | Quantity | Category | Quantity |
|------------------|--------------------|---|------------------------|
| rock wool | 5 kg | usage | 1600 h y ⁻¹ |
| cast iron | 12 kg | efficiency | 82% |
| copper | 5,6 kg | boiler lifetime | 20 y |
| Steel low allw | 500 kg | pellet cons. | 8,8 t y ⁻¹ |
| polyethylene | 1,2 kg | silos supplies | 2 y ⁻¹ |
| concrete | 3,4 m ³ | silos volume | 6,8 m ³ |
| Substance | | mg MJ⁻¹ of thermal energy | |
| CO | | 146,34 | |
| TOC | | 3,66 | |
| CH ₄ | | 0,67 | |
| PAH | | 0,07 | |
| particulate | | 19,51 | |
| NO _x | | 85,37 | |
| NMVOC | | 0,49 | |

Table 6: Results for the damage categories of pellet chain (EcoIndicator 99).

| Damage category | Biomass cultivation (mPt) | Wood chip transport (mPt) | Pellet transport (mPt) | Wood pelleting (mPt) | Pellet combustion (mPt) | TOTAL (mPt) |
|-------------------------|----------------------------------|----------------------------------|-------------------------------|-----------------------------|--------------------------------|--------------------|
| Human health | 0,436 | 0,063 | 0,018 | 0,400 | 0,524 | 1,440 |
| Ecosyst. quality | 0,519 | 0,013 | 0,005 | 0,188 | 0,051 | 0,776 |
| Resources | 0,546 | 0,100 | 0,044 | 0,259 | 0,020 | 0,970 |
| TOTAL | 1,500 | 0,176 | 0,067 | 0,847 | 0,594 | 3,190 |

Table 7: Results for the impact categories for pellet chain (EcoIndicator 99).

| Impact category | Biomass cultivation (μPt) | Wood chip transport (μPt) | Pellet transport (μPt) | Wood pelleting (μPt) | Pellet combustion (μPt) | TOTAL (μPt) |
|------------------------|----------------------------------|----------------------------------|-------------------------------|-----------------------------|--------------------------------|--------------------|
| Carcinogens | 130,0 | 2,8 | 1,5 | 19,0 | 18,0 | 171,3 |
| Resp. organics | 0,15 | 0,07 | 0,02 | 0,35 | 0,12 | 0,7 |
| Resp. inorganics | 270,0 | 54,0 | 14,0 | 360,0 | 500,0 | 1.198,0 |
| Climate change | 35,0 | 6,3 | 2,6 | 15,0 | 5,5 | 64,4 |
| Radiation | 0,40 | 0,02 | 0,01 | 1,30 | 0,75 | 2,5 |
| Ozone layer | 0,0190 | 0,0044 | 0,0020 | 0,0110 | 0,0003 | 0,0367 |
| Ecotoxicity | 28,0 | 3,6 | 1,7 | 17,0 | 11,0 | 61,3 |
| Acidif/ Eutroph. | 110,0 | 8,5 | 2,4 | 50,0 | 39,0 | 209,9 |
| Land use | 380,00 | 0,93 | 0,40 | 120,00 | 0,77 | 502,1 |
| Minerals | 12,00 | 0,65 | 0,35 | 9,00 | 20,00 | 42,0 |
| Fossil fuels | 540,0 | 100,0 | 44,0 | 250,0 | - 0,82 | 933,2 |
| TOTAL | 1.505,57 | 176,87 | 66,98 | 841,66 | 594,32 | 3.185,40 |

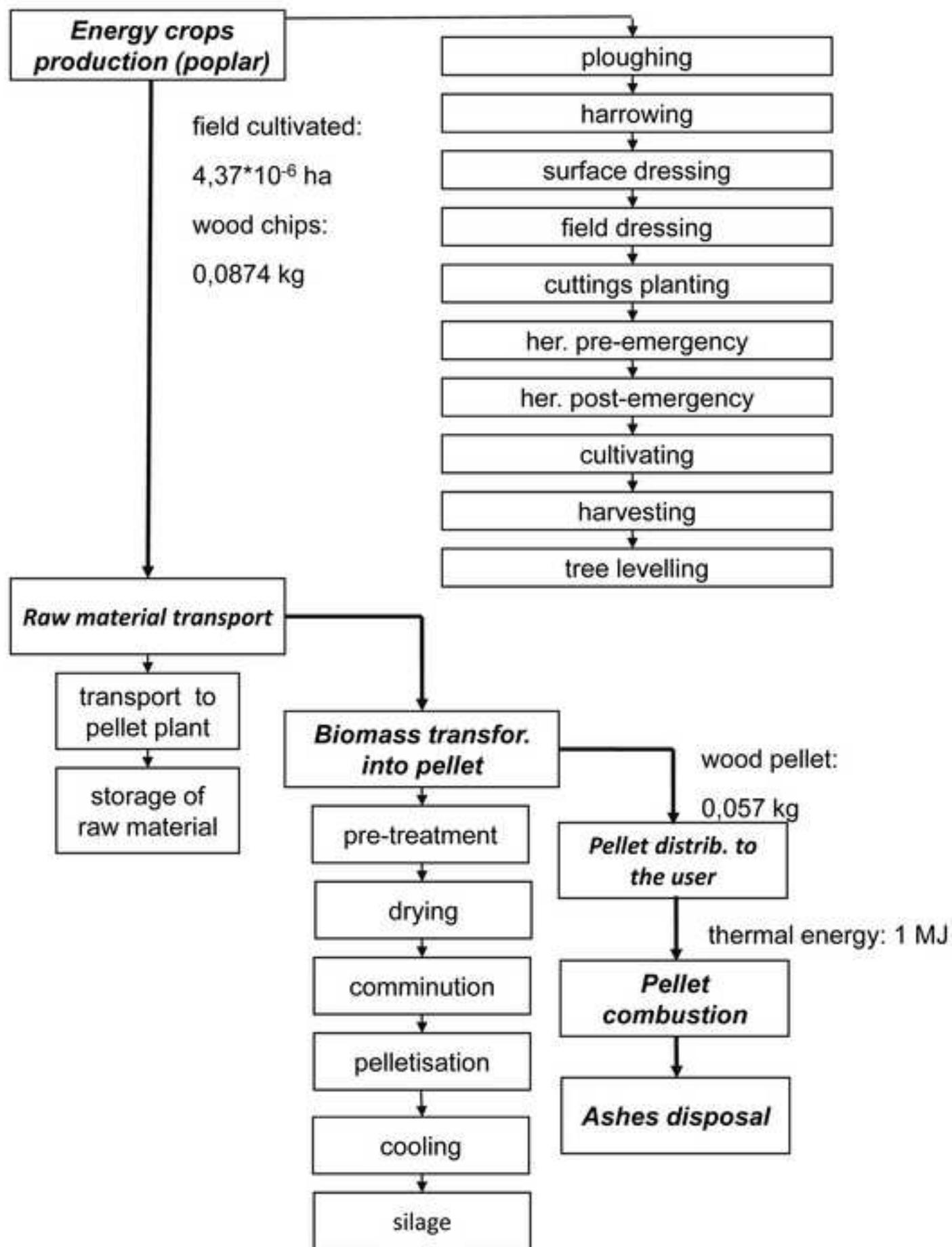
Tab. 8: Results for the damage categories for pellet chain (EPS 2000).

| Damage category | Biomass cultivation (μPt) | Wood chip transport (μPt) | Pellet transport (μPt) | Wood pelleting (μPt) | Pellet combustion (μPt) | TOTAL (μPt) |
|-------------------------------|----------------------------------|----------------------------------|-------------------------------|-----------------------------|--------------------------------|--------------------|
| Human Health | 1.800,00 | 340,00 | 1.800,00 | 110,00 | 6.700,00 | 10.750,00 |
| Ecosystem Produciton Capacity | - 40,00 | - 2,70 | - 8,50 | - 1,10 | - 4,20 | - 56,50 |
| Abiotic Stock Resources | 6.200,00 | 410,00 | 3.800,00 | 200,00 | 5.100,00 | 15.710,00 |
| Biodiversity | 16,00 | 2,40 | 19,00 | 0,98 | 2,80 | 41,18 |
| TOTAL | 7.976,00 | 749,70 | 5.610,50 | 309,88 | 11.798,60 | 26.444,68 |

Tab. 9: Results for the impact categories for pellet chain (EDIP).

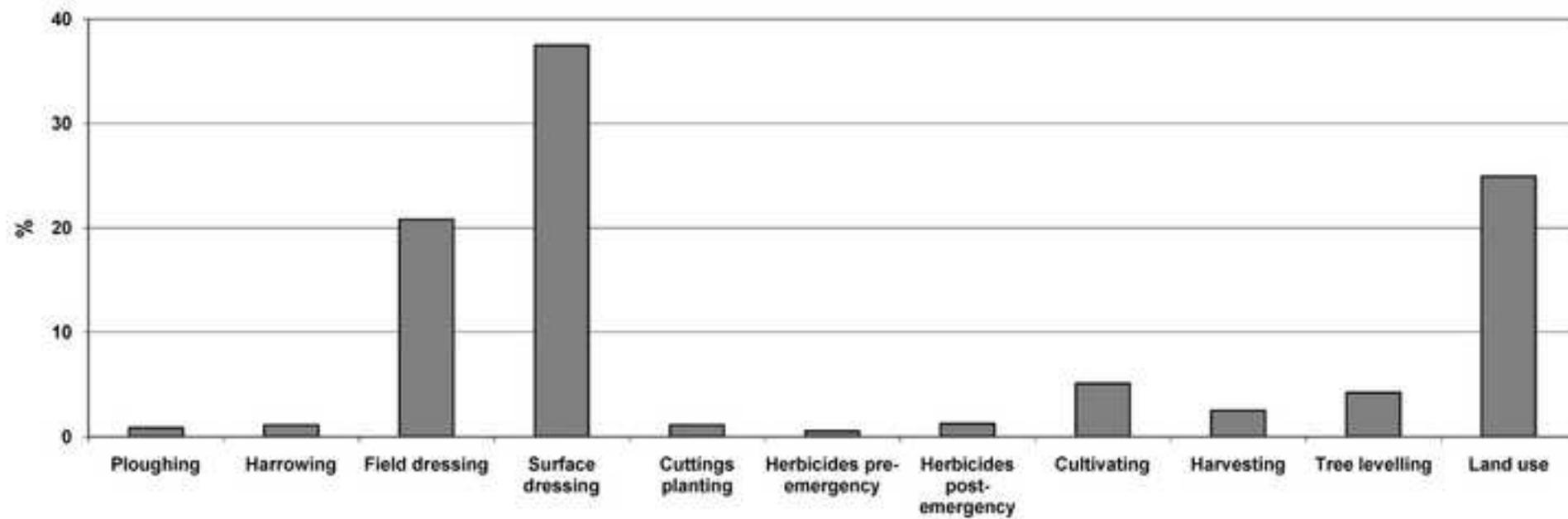
| Impact category | Biomass cultivation (μPt) | Wood chip transport (μPt) | Pellet transport (μPt) | Wood pelleting (μPt) | Pellet combustion (μPt) | TOTAL (μPt) |
|---------------------------|----------------------------------|----------------------------------|-------------------------------|-----------------------------|--------------------------------|--------------------|
| Global Warming | 1,30 | 0,23 | 0,57 | 0,10 | 0,22 | 2,42 |
| Ozone Depletion | 0,08 | 0,01 | 0,04 | 0,01 | 0,00 | 0,14 |
| Acidification | 2,00 | 0,16 | 0,90 | 0,05 | 0,67 | 3,78 |
| Eutrophication | 2,40 | 0,10 | 0,77 | 0,03 | 0,49 | 3,79 |
| Photochemical Smog | 0,04 | 0,01 | 0,08 | 0,00 | 0,28 | 0,42 |
| Ecotoxicity water chronic | 44,00 | 9,70 | 35,00 | 4,40 | 27,00 | 120,10 |
| Ecotoxicity water acute | 36,00 | 7,90 | 21,00 | 3,60 | 6,60 | 75,10 |
| Ecotoxicity soil chronic | 9,10 | 0,55 | 8,80 | 0,26 | 6,10 | 24,81 |
| Human toxicity air | 0,99 | 0,27 | 2,10 | 0,11 | 2,00 | 5,47 |
| Human toxicity water | 23,00 | 2,30 | 11,00 | 1,10 | 26,00 | 63,40 |
| Human toxicity soil | 310,00 | 70,00 | 750,00 | 34,00 | 840,00 | 2.004,00 |
| Bulk Waste | - | - | - | - | - | - |
| Hazardous Waste | - | - | - | - | - | - |
| Radioactive Waste | - | - | - | - | - | - |
| Slags/Ashes | - | - | - | - | - | - |
| TOTAL | 428,91 | 91,24 | 830,26 | 43,65 | 909,36 | 2.303,42 |

Figure
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Figure

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