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# Life Cycle Assessment of electricity production from poplar energy crops compared with conventional fossil fuels

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**Abstract**

The environmental impact of electric power production through an Integrated Gasification Combined Cycle (IGCC) fired by dedicated energy crops (poplar Short Rotation Forestry (SRF)) is analysed by a Life Cycle Assessment approach. The results are compared with the alternative option of producing power by conventional fossil fueled power plants. The energy and raw materials consumption and polluting emissions data both come from experimental cases. Thermodynamic models are applied for simulation of the energy conversion system. The results establish relative proportions for both consumption and emissions of the two energy systems, in detail. Considerable differences emerge about the environmental impact caused by the different gasification conditions. The evaluation of the environmental effects of residues of the pesticides in ground/surface water and in the soil required a particular care, as well as the characterisation of all chemicals (herbicides, fungicides and insecticides) used for the crops. © 1999 Elsevier Science Ltd. All rights reserved.

*Keywords:* Life Cycle Assessment; Biomass; Energy crops; Poplar

## 1. Introduction

Since 1987, when the World Commission on Environment and Development [1] defined as sustainable development the one '... that meets the needs of the present without compromising the ability of future generations to meet their own needs', up to the recent Kyoto World

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Summit in December 1997, when greenhouse gases reductions have been adopted for the next decade, European commissions have ratified numerous projects having as key targets the improvement of energy efficiency and protection of the environment from the effects of power generation. Renewable energy sources promotion is viewed as an important issue to achieve these objectives. According to EEC policies, the contribution of renewable sources to the European community power mix should increase from 6 to 12% within 2010.

The world achievable biomass power is estimated to be approximately 70 Gtep/year [27], which renders biomass the most significant among renewable sources. Within the European projects JOULE-THERMIE, different systems for the production of electric power from agricultural biomass are in execution or under prototyping. One of the most interesting solutions in terms of global efficiency and economic feasibility is achieved by gasifying biomass to produce a low/medium heating value gas, which is then used as a fuel for a gas turbine combined cycle. For this solution, the evaluation of the environmental impact associated with resources and energy consumption (crops production, transport and biomass conversion) seemed to be of interest. Life Cycle Analysis (LCA) was considered the most useful tool to this end.

## 2. What is LCA?

LCA is intended to be a quasi-objective process for evaluation of the environmental loads caused by a product, process or single activity. The evaluation is obtained through quantification of the energy and materials consumption and wastes releases into the environment within the entire life cycle of the system. Obviously, this should include computation of the effects of extraction of the raw materials, manufacturing processes, transport and distribution, use, reuse, recycling and/or final waste disposal [2–5].

According to Fig. 1, this evaluation can be split into four steps:

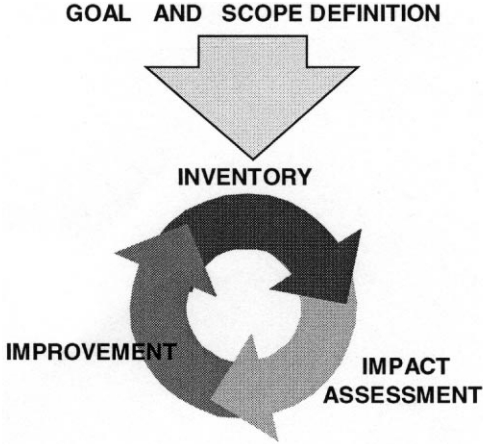


Fig. 1. Life cycle assessment steps.

1. *Goal and Scope Definition*. This means definition of system boundaries, details accuracy and data quality, functional units and impact models to be used for the analysis [6,7].
2. *Inventory Analysis*. All necessary data must first be available from literature surveys or direct measurements and classified according to the type of environmental impact (for instance, distinguishing between air, water and soil emissions, solid wastes, energy and materials consumption). The collected data must be allocated according to each considered process output unit [7].
3. *Impact Assessment*. All data need to be first characterised in terms of the considered environmental effects [8]. This is followed by normalisation of the results to obtain nondimensional values which allow measuring the impact. According to the used impact model, it is possible to evaluate a global environmental score through appropriate weighting factors.
4. *Improvement Analysis*. In order to propose improvements in the environmental performance, the most significant impact sources must be determined and possible alternatives and/or modifications considered for the process [9].

## 3. The impact model

As a model for the impact evaluation, the Eco-Indicator 95 methodology [10–12] was applied. This method has been developed within the national Dutch program NOH about waste recycling by Leiden (CML), Delft (TU and CE) and Amsterdam Universities (IVAM-ER). Table 1 summarises the environmental effects considered within the Eco-Indicator 95, together with their units of measurement (equivalent substances).

Once the characterisation and normalisation steps are accomplished, it is possible to calculate the Eco-It value as a global environmental score, scaling the environmental profile

Table 1
Eco-Indicator 95 impact model

| Effect category | Environmental effect | | Unit |
|---|---|---|---|
| Environment protection | Greenhouse | | eq. kg $CO_2$ |
| | Ozone layer depletion | | eq. kg CFC11 |
| | Acidification | | eq. kg $SO_2$ |
| | Eutrophication | | eq. kg $PO_2$ |
| Health safe | Smog | Summer | eq. kg $C_2H_4$ |
| | | Winter | kg SPM |
| | Toxic substances | Heavy metals | eq. kg Pb |
| | | Carcinogens | eq. kg B(a)P |
| | | Pesticides | kg act. sub. |
| Resource depletion | Solid waste | | kg |
| | Energy consumption | | MJ (LHV) |

with appropriate weighting factors which express the relative importance among the effects. Since assignment of the weights is affected to a certain degree by arbitrary choices, this last step is often avoided or postponed to the very last possible moment (e.g., for comparisons among different options).

Within the impact model, special attention was devoted to the effects of chemical substances, commonly used by agricultural crops. The impact was, in this case, evaluated by building an equivalent global 'pesticides' effect.

## 4. Energy crops production

### *4.1. Land requirements*

Land usage for energy crops must be selected according to not only technical issues, but considering also social and economic criteria [13]. The EEC agricultural policies point out the uncultivated lands having low financial income as the most appropriate for this use [14]. Utilisation of land dedicated to feed crops raising is possibly to be avoided.

Agricultural land requirements are normally estimated by the measure of some chemical, physical and land form parameters [15]. Among these, good land drainage and slight dip are of basic importance for our purpose. Excessive dip makes, therefore, mechanisation of SRF (Short Rotation Forestry) difficult (mechanisation is essential for SRF economic feasibility). Slow land drainage reduces roots oxygen availability, strongly compromising vegetal growth and biomass yield.

Table 2
Nursery and SRF operations (yearly repetitions)

| Operation | Nursery | | | SRF | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Year | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 |
| Plowing | 1 | | | 1 | | | | | | | |
| Field dressing | 1 | | | 1 | | 1 | | 1 | | 1 | |
| Harrowing | 1 | | | 1 | | | | | | | |
| Cuttings planting | 1 | | | 1 | | | | | | | |
| Herbicides field distribution | 1 | 1 | 1 | 1 | | 1 | 1 | 1 | 1 | 1 | 1 |
| Surface dressing | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Herbicides local distribution | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| Cultivating | 4 | 4 | 4 | 4 | 2 | 4 | 2 | 4 | 2 | 4 | 2 |
| Antiparasitic agents application | 2 | 2 | 2 | | | | | | | | |
| Surface irrigation | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 | 2 |
| Nursery trees harvesting | 1 | 1 | 1 | | | | | | | | |
| Nursery trees transportation | 1 | 1 | 1 | | | | | | | | |
| Cuttings preparing | 1 | 1 | 1 | | | | | | | | |
| Biomass harvesting | | | | | 1 | | 1 | | 1 | | 1 |
| Tree levelling | | | 1 | | | | | | | | 1 |

Table 3
Chemicals and machinery for plantation operations

| Operation | Machinery | Engine power (kW) | Substance | Quantity (kg/ha) | Execution time (h/ha) | |
|---|---|---|---|---|---|---|
| | | | | | Nursery | SRF |
| Plowing | Gangplow | 80 | | | 1.85 | 1.85 |
| Harrowing | Vertical spike-tooth harrow | 80 | | | 0.69 | 0.69 |
| Cuttings planting | Transplanter | 51 | | | 11.43 | 11.43 |
| Field dressing | Centrifugal dressing spreader | 51 | 8-24-24 | 500 | 0.45 | 0.45 |
| Surface dressing | Centrifugal dressing spreader | 51 | UREA | 218 | 0.41 | 0.41 |
| Herbicides pre-emergency | Dusting | 51 | METOLACLOR | 1.7 | 0.26 | 0.26 |
| | | | LINURON | 0.5 | | |
| | | | PENDIMETALIN | 0.8 | | |
| Herbicides post-emergency | Dusting | 51 | PIRIDATE | 1.125 | 1.19 | 1.19 |
| | | | FLAZIFOP-P-BUTYL | 0.665 | | |
| | | | WATER-BASED | 1 | | |
| Cultivating | Disk harrow | 51 | | | 0.78 | 0.78 |
| Antiparasitic agents application | Dusting | 51 | CHLORPYRIFOS | 0.120 | 1.36 | 1.36 |
| | | | CYPERMETHRIN | 0.012 | | |
| | | | FENITROTHION | 0.285 | | |
| Surface irrigation | Close-coupled pump | 75 + 51 | WATER | 350,000 | 3.12 | 3.12 |
| Nursery trees harvesting | Cutter, lopping shears | 51 (228) | | | 2.65 | 1.23 |
| Nursery trees transportation | Grabbing crane | 80 | | | 26.29 | |
| Cuttings preparing | Electric powered saw | 1.5 | | | 26.5 | |
| Tree levelling | Horizontal spike-tooth harrow | 80 | | | 4.84 | 4.84 |

### 4.2. Clonus selection

Appropriate arboreal species for cultivation of feedstock crops are limited to poplar, willow and eucalyptus. According to recent Italian experiments [15], poplar Lux clonus seems to permit the best biomass yield, considering the typical weather and composition of soil. This work refers to those experimental data and to the agricultural operations for the above mentioned cultivation grown on an eight-year SRF.

### 4.3. Biomass production cycle

The biomass production cycle is based on harvesting two-year-old poplar trees. SRF is preceded by a three-year nursery cultivation aimed at production of cuttings. Table 2 collects the basic operations of the nursery and SRF cycles, together with their replication/year number.

### 4.4. Plantation substances and necessary machinery

With reference to the activities described in Table 2, Table 3 shows the usage of chemical antiparasitic agents, of nitrogen compounds fertilisers and the power consumption connected with the machinery necessary for the described operations. The typical execution time is also reported, so that fuels consumption and polluting emissions can be calculated.

### 4.5. Biomass yield (Table 4)

The achievable biomass yield is estimated to be about 20 dry Mg/ha/year, according to published experimental results [14,16,17]. The net available quantity of biomass is about 16 dry Mg/ha/year as a result of natural drying during stockage.

### 4.6. Characterisation of chemicals used for the crops

In order to estimate the persistence of agriculture-used chemicals, the dispersion models can be classified according to:

1. Water pollution: a certain amount of the plantation pesticides can reach surface and ground water through percolation and run-off mechanisms. The ground water percolation quantity is assumed to vary between 0.5% [18,19] and 2% [20] of the applied substance, whereas the run-off mechanism can transport from 0.01% [19] to 1% [21].

Table 4
Biomass yield and characteristics

| Biomass yield (Mg/ha/year) | LHV (MJ/kg) | HHV (MJ/kg) | Humidity (%) | After drying humidity (%) |
|---|---|---|---|---|
| 20 | 17.7 | 19 | 60 | 15–20 |

2. Air pollution: the percentage quantity directly dispersed to air is very difficult to determine. Some authors report exceedingly low values [18], while some others assume about 5% of the substance [22]. Considering that all the chemicals dispersed in air are rapidly degraded or re-deposited to the ground, the first choice is the less environmentally advantageous and was assumed throughout this study.
3. Soil pollution: soil persistence toxicity has been evaluated only for substances having DT90 (degrading time of 90% of active substance) greater than 100 days.

According to the above considerations, Fig. 2 shows the relative balance of aero-dispersed chemical substances.

With reference to European and Italian Laws (DPR1255/1968, CE78/631), four toxicity classes are considered for agricultural chemical substances. This classification is a consequence of the substance LD50 oral measure (lethal dose for 50% of guinea pigs sample). Table 5 reports this law classification for the used substances.

According to EEC guidelines for the environment, the characterisation model employs oral and dermal LD50 values as a criterion to assess substance toxicity. In detail, the limit between toxic and obnoxious substances is fixed at oral LD50 levels of 50 mg/kg if solid, or 200 mg/kg if liquid, with reference to water pollution. On the other hand, for soil pollution, the limit dermal LD50 value of 100 mg/kg was used for both solid and liquid substances.

For instance, suppose a substance has an oral LD50 level of 3300 mg/kg and a dermal LD50 of 2400 mg/kg. According to Fig. 2, suppose 90% of the applied quantity contributes to soil pollution and 3% to water pollution. The equivalent quantity of polluting substance can be calculated as:

$$(0.03 \times 200/3300 + 0.90 \times 100/2400) \times \text{mass}$$

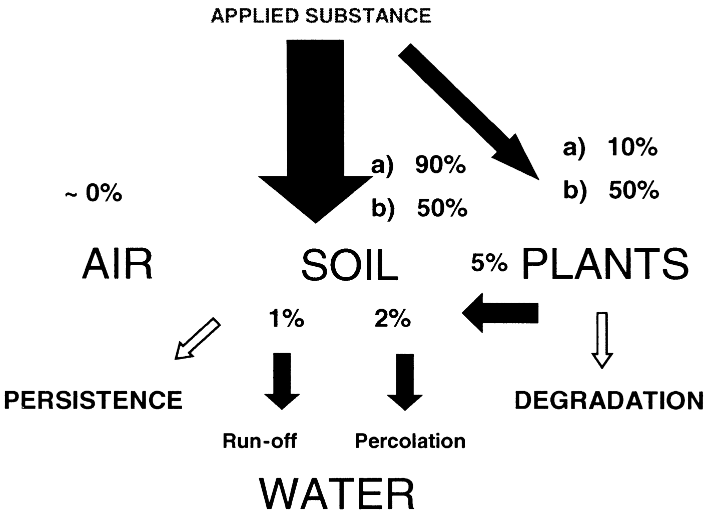


Fig. 2. Pesticides residues model: (a) pre-emergency application, (b) post-emergency application.

Table 5
Pesticides toxicology

| Active substance | Class | Type | Oral LD50 (mg/kg) | Dermal LD50 (mg/kg) |
|---|---|---|---|---|
| Metolaclor | III | Herbicides | 2780 | 3170 |
| Linuron | II–III | Herbicides | 1500 | 5000 |
| Pendimetalin | III | Herbicides | 3000 | 5000 |
| Piridate | III | Herbicides | 2400 | 3400 |
| Fluazifop-p-butyl | III | Herbicides | 3300 | 2400 |
| Chlorpyrifos | II | Insecticide | 80 | 200 |
| Cypermethrin | II | Insecticide | 900 | 4800 |
| Fenitrothion | II | Insecticide | 200 | 1000 |
| Glufosinate a. | III | Herbicide | 1620 | 4000 |

in the case of a liquid substance, or as:

$$(0.03 \times 50/3300 + 0.90 \times 100/2400) \times \text{mass}$$

in the case of a solid substance.

## 5. Transportation of biomass to power plant

Diesel trailers (40 Mg load) were considered for biomass transport. An average distance of 75 km from biomass stocks to power plant was assumed [29,30]. Energy consumption and

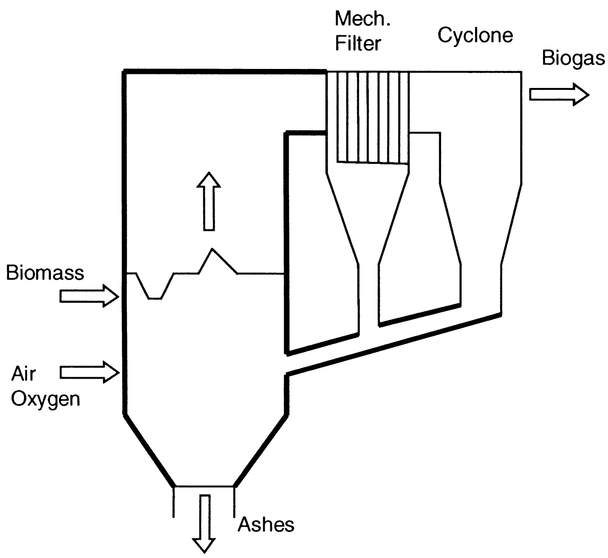


Fig. 3. PFB gasifier scheme and biogas pre-filtering.

emissions caused by extraction, processing, transport and combustion of fuel for transport were completely taken into account.

## 6. Description of the conversion system (biomass gasification) (Fig. 3)

A low or medium heating value gas is produced by a pressurised fluid bed (PFB) gasifier with an air or oxygen stream (steam injection is not necessary because of the biomass humidity). The LHV of the gas is sensitive to both the oxidising agent and biomass humidity.

The gasifier includes mechanical filters and an effective cyclone for removing large particles from the gas. A further filtration step is also necessary in order to remove fine particles (smaller than 10 $\mu$m) which should not be ingested by the gas turbine. High-temperature ceramic filters allow avoiding cooling of the gas and are, therefore, recommended [25].

Four different gasification conditions were considered, which are listed in Table 6.

The biomass composition is typical of a poplar crop and is reported in Table 7.

The ashes produced by the gasification have not been taken into account as a polluting solid waste because of their many possible industrial uses. Their typical composition is reported in Table 8 [23].

A well-established simulation model, developed at the University of Florence, was used for the gasifier. The model uses a zero-dimensional equilibrium approach and has demonstrated acceptable prediction capabilities for both gas heating value and chemical composition with special reference to fluidised bed gasifiers [24].

The biogas and oxidiser flow rates are collected in Table 9. Table 10 collects the biogas molecular composition for the four reference cases considered.

## 7. Gas turbine topping cycle and steam turbine bottoming cycle

The biogas is used as a fuel in a gas/steam combined cycle power plant. The combined cycle for electric power production is basically represented in Fig. 4. The plant layout is relatively simple. The high humidity of the biomass avoids the necessity of steam extraction for the gasifier and reduces the gasifier/power plant interaction to a simple serial mode.

The cycle simulation was performed using a modular model for gas-turbine-based power

Table 6
Gasification conditions

| Code | Biomass humidity (%) | Oxidising agent | $T$ (K) | $p$ (bar) |
|---|---|---|---|---|
| 15 AIR | 15 | Air | 1050 | 15 |
| 20 AIR | 20 | Air | 1050 | 15 |
| 15 $O_2$ | 15 | Oxygen | 1050 | 15 |
| 20 $O_2$ | 20 | Oxygen | 1050 | 15 |

Table 7
Biomass molecular composition (mass %)

| Humidity | Carbon | Oxygen | Nitrogen | Hydrogen | Sulphur |
|---|---|---|---|---|---|
| 15% | 41.18 | 37.13 | 1.71 | 4.97 | 0.01 |
| 20% | 38.76 | 34.95 | 1.6 | 4.68 | 0.01 |

Table 8
Produced ashes composition (mass %)

| $Al_2O_3$ | CaO | $Fe_2O_3$ | $K_2O$ | MgO | $Na_2O$ | $SiO_2$ |
|---|---|---|---|---|---|---|
| 8.7 | 7.7 | 4.3 | 2.6 | 1.8 | 0.8 | 36.9 |

plants developed at the University of Florence [24]. Table 11 reports the basic power plant parameters under design conditions, while Table 12 shows the stack gas composition.

## 8. Biomass-fueled energy compared to fossil-fueled energy environmental impact

### *8.1. Biomass production impact*

Fig. 5 shows the most significant releases to the environment due to biomass production.

$CO_2$ emissions amount to 7330 kg/ha/year as a whole. Carbon dioxide and monoxide are mostly due to the exhausts of Diesel fueled machinery. The manufacturing and use of nitrogen compounds fertilisers cause ammonia and methane emissions. The ground water pollution is due to acids and nitrogen compounds dispersion. These toxic releases are small in terms of flow rate, but of high polluting potential. Therefore, they contribute significantly to the overall environmental impact. Fig. 6 shows the characterisation and normalisation of the data of Fig. 5. The high eutrophication peak is totally due to the utilisation of nitrogen-compounds fertilisers.

### *8.2. Comparison of different gasification conditions*

As is well known, oxygen steam gasification permits a higher conversion efficiency, allowing more power production with the same biomass flow rate. However, this higher efficiency seems to be not sufficient to make this solution environmentally advantageous (see Fig. 7). The basic problem is that power for the oxygen production was assumed as taken from the electric grid and, thus, produced by means of fossil fuels, which is consistent with the hypotheses about the penetration of biomass produced electricity on the European marketplace. The results are, thus, strongly dependent on the considered (current or future) national power mix.

Table 9
Biogas and air/oxygen stream flow rates (per biomass flow rate unit)

| Condition | Biogas flow rate | Air flow rate | Oxygen flow rate |
|---|---|---|---|
| 15 AIR | 2.8672 | 1.8672 | |
| 15 $O_2$ | 1.392 | | 0.392 |
| 20 AIR | 2.7577 | 1.7577 | |
| 20 $O_2$ | 1.3689 | | 0.3689 |

Table 10
Biogas molecular composition (mass %) and low heat value (kJ/kg)

| Condition | $CO_2$ | $H_2O$ | CO | $CH_4$ | C(s) | $N_2$ | $H_2$ | LHV |
|---|---|---|---|---|---|---|---|---|
| 15 AIR | 0.2279 | 0.08821 | 0.14699 | 0.00534 | 0.0144 | 0.50522 | 0.01194 | 3482 |
| 15 $O_2$ | 0.45655 | 0.16703 | 0.28668 | 0.028 | 0.02734 | 0.01238 | 0.02202 | 7610 |
| 20 AIR | 0.23506 | 0.10041 | 0.13983 | 0.00508 | 0.01263 | 0.49445 | 0.01254 | 3376 |
| 20 $O_2$ | 0.46006 | 0.18831 | 0.26753 | 0.02571 | 0.02363 | 0.01177 | 0.02299 | 7225 |

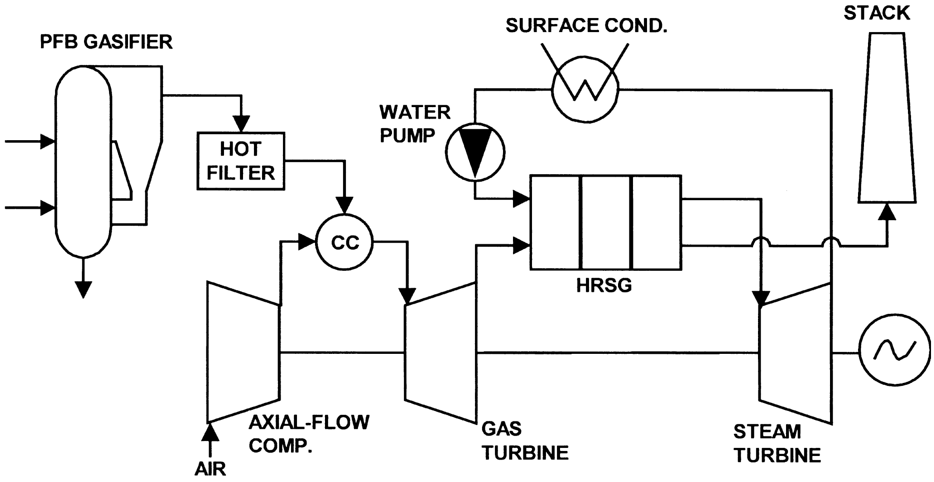


Fig. 4. IGCC power plant scheme.

Table 11
Normal operation power plant parameters

| | |
|---|---|
| Biogas gasifier output pressure (bar) | 15 |
| Biogas gasifier output temperature (°C) | 800 |
| Biogas filter output pressure (bar) | 13.5 |
| Biogas filter output temperature (°C) | 700 |
| Gas turbine pressure ratio | 12 |
| Biogas overpressure (%) | 10 |
| Gas turbine high temperature (°C) | 1077 |
| Steam superheater output pressure (bar) | 70 |
| Steam superheater output temperature (°C) | 532 |
| Superheater approach ΔT (°C) | 30 |
| Steam turbine output pressure (bar) | 0.1 |
| Exhaust gas output pressure (bar) | 1.01 |

Table 12
Stack gas molecular composition (per flow rate unit) and temperature *T* (K)

| Condition | $O_2$ | $N_2$ | $H_2O$ | $CO_2$ | *T* |
|---|---|---|---|---|---|
| 15 AIR | 0.60 | 3.22 | 0.24 | 0.54 | 439 |
| 15 $O_2$ | 1.45 | 6.40 | 0.51 | 1.11 | 438.5 |
| 20 AIR | 0.57 | 3.11 | 0.26 | 0.53 | 438.3 |
| 20 $O_2$ | 1.37 | 6.05 | 0.53 | 1.08 | 437.4 |

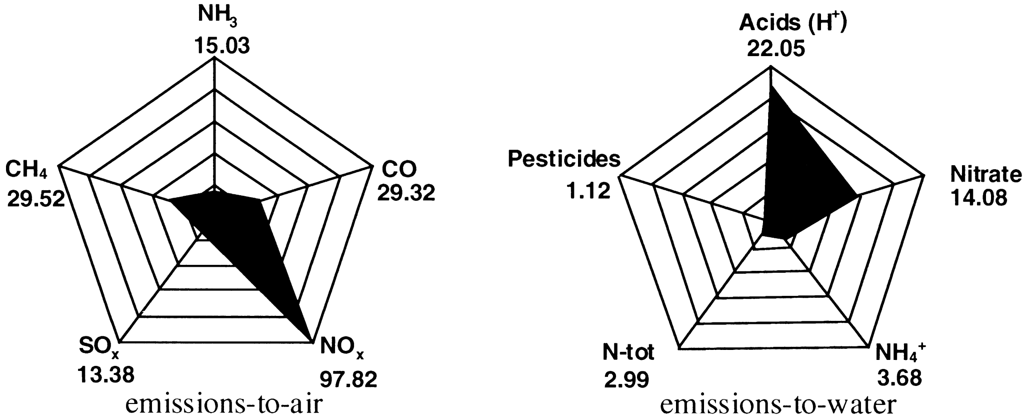


Fig. 5. Polluting emissions (kg/ha/year).

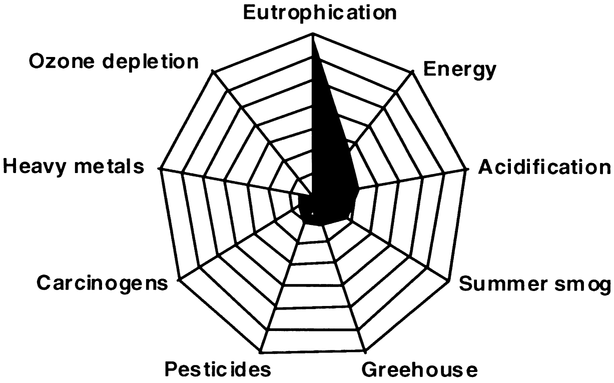


Fig. 6. Normalised environmental effects due to biomass production.

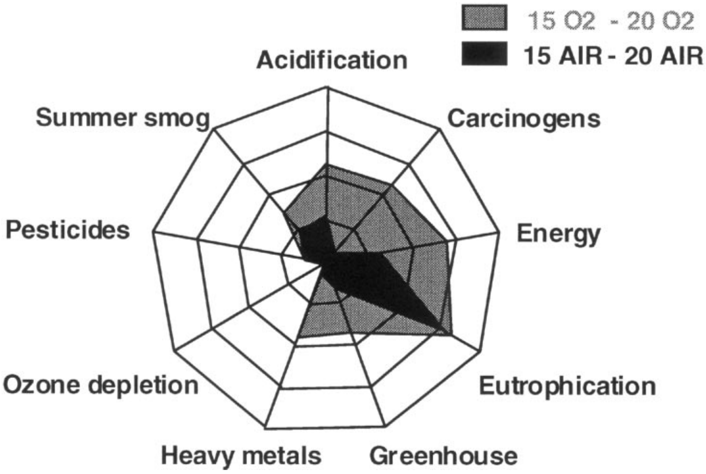


Fig. 7. Normalised environmental effects due to different gasification conditions.

## *8.3. Comparison with fossil-fueled power production*

Available data about emissions and resources consumption caused by 1 MWh fossil fuels electric power production (with reference to a power mix composed of 50% electric power from coal and 50% electric power from oil) allowed a comparison with the calculated results for the whole biomass energy utilisation cycle. Fig. 8 reports the comparison for air and water life cycle polluting emissions.

The equivalence between $CO_2$ biomass combustion emissions (inside a continuous biomass cultivation cycle) and $CO_2$ absorption during growth of plants is commonly accepted. For this reason, $CO_2$ emissions were not considered for biomass combustion (but the emissions for Diesel fuel consumption or for the production of chemicals were taken into account). The

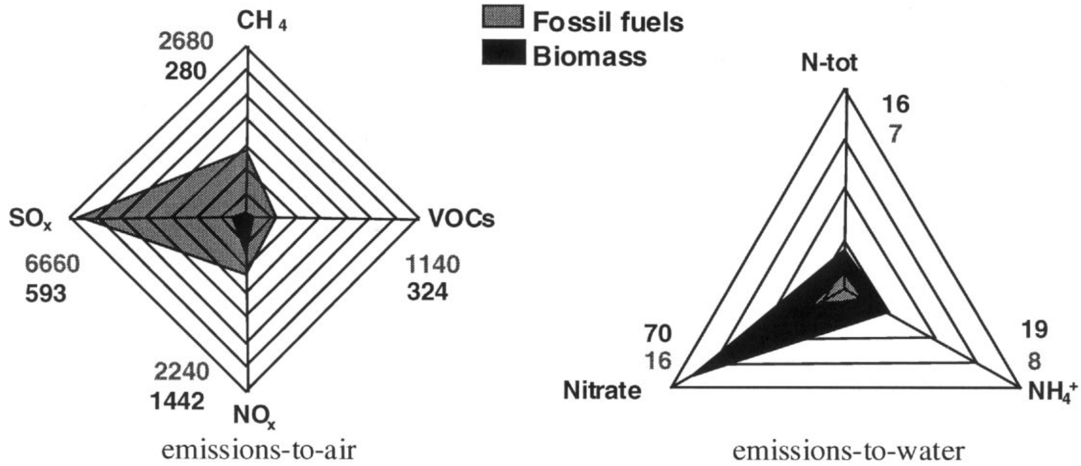


Fig. 8. Polluting emissions (g/MWh).

whole $CO_2$ emission factor amounts to 110 kg/MWh for the biomass-fueled system and to 930 kg/MWh typical for fossil-fueled systems, showing a reduction ratio of about 8.5 to 1.

According to the Eco-Indicator 95 impact model, normalised results and environmental total scores are shown in Fig. 9.

## 9. Life-cycle efficiency

The biomass conversion system produces 1 MWh electric power from 633 kg of biomass (LHV = 17.7 MJ/kg). Thus, the overall conversion system efficiency can be calculated as:

$$\eta = \frac{3600}{17.7 \times 633} = 0.321 \tag{1}$$

This efficiency does not account for life cycle energy and resources consumption.

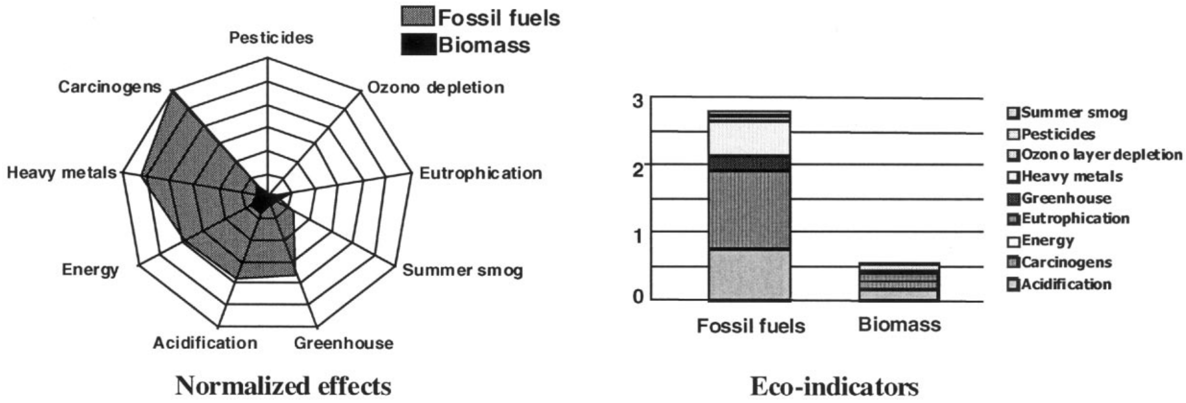


Fig. 9. Electric power production from fossil fuels and from biomass.

With reference to a life cycle analysis, a more appropriate definition for overall system efficiency is [17]:

$$\eta_{LC} = \frac{E_g - E_u}{E_b} \tag{2}$$

where $E_g$ is electric energy delivered to grid; $E_u$ is energy consumed by upstream processes (renewable sources energy consumption excluded); and $E_b$ is feedstock energy of fuel fed to power plant.

According to the last definition, the life cycle efficiency for the biomass fueled system was calculated as:

$$\eta_{LC} = \frac{3600 - 2256.8}{17.7 \times 633} = 0.119 \tag{3}$$

It is finally important to recognise that the life cycle efficiency for the alternative fossil-fueled system gives a negative result (overall energy deficit).

## 10. Conclusions

Considering the results obtained, some possible issues have been identified in order to improve environmental efficiency. With reference to biomass production, the most negative environmental effects are caused by the usage of chemicals and fertilisers. Thus, improvements are necessarily based on optimisation of the ratio *biomass yield/applied fertilisers* and on biological antiparasitic solutions. The use of Biodiesel as a fuel for agricultural machinery could further reduce $CO_2$ emissions and the life cycle environmental impact. With reference to gasification conditions, the use of air as an oxydiser causes 2 to 7 times lower environmental effects than in the case of oxygen gasification. However, 99% of that is due to the electricity consumption to produce the oxygen. According to EEC expectations for year 2010, a 12% power mix from renewable sources scenario makes this difference not very significant. Oxygen self-production inside the biomass fueled power plant is economically feasible for a plant size not lower than 100 $MW_e$ (10–15% of the produced electricity feeds the oxygen production system) [26]. This last solution would generate a lower environmental impact, but about 1520 Mg/day of biomass are needed to feed a 100 $MW_e$ power plant. Under this assumption, 7200 h/year electric power production is achievable with a dedicated 28,500 ha SRF (e.g., amounting to 4% of the whole Tuscany agricultural lands).

The social impact on the rural economy, and the economic benefits caused by the introduction of energy crops, should be taken into account in a more detailed analysis. From a purely economic point of view, the described system would never be competitive with respect to conventional energy conversion systems unless the environmental costs of life cycle energy conversion were correctly taken into account while considering environmental sustainability [28].

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