BIO-ENERGY CHAINS FROM PERENNIAL CROPS IN SOUTH EUROPE

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ABSTRACT: This work refers to the EU project 'Bioenergy chains' (Contract No: ENK6-CT2001-00524). The overall objective of this project is to evaluate, in terms of technical, financial/economic and environmental feasibility, the whole bioenergy chain from biomass production to thermochemical conversion for a number of perennial energy crops carefully selected to ensure, by successive harvesting, a year-round availability of raw material. According to the data collected so far, the establishment, cultivation and harvesting of all four species were performed successfully, without needing new agricultural methods. The chemical composition of the perennial crops is closer to straw than woody biomass fuels therefore technologies for thermal conversion of straw should be considered for these crops. Overall costs and environmental implications affiliated with the production and use of the crops were estimated and best options (combinations of crops, chosen technology etc.) for each region or country were identified.
Key words: perennial energy crops, thermochemical conversion, economic aspects, LCA, EIA

1 INTRODUCTION

In the whole bioenergy chain, biomass production – processing – conversion, considerable time and funds have been spent so far on research solely for biomass production or energy conversion processes. Little attention has been paid yet to measuring and evaluating the performance of perennial and annual crops in an integrated bioenergy chain.

Use of a mixture of crops offers the potential for a year-round operation without the need to store large quantities of materials and feeding systems developed for energy crops and related materials would be capable of handling a wide range of materials with comparable handling characteristics.

This work refers to the EU project 'Bioenergy chains', Contract No: ENK6-CT2001-00524 [1].

2 APPROACH

The objective of this project is to define and evaluate complete bioenergy chains from biomass production to thermochemical conversion for production of valuable energy products. Four perennial energy crops, *Arundo donax* (Giant reed), *Cynara cardunculus* (cardoon), *Miscanthus x giganteus* (Miscanthus), *Panicum virgatum* (Switchgrass), are grown in southern Europe (Greece, Italy, France and Spain), which have been carefully selected to provide a year-round availability of raw material. These were processed thermally by combustion, gasification and fast pyrolysis. The complete chains were evaluated in technical, financial/economic and environmental terms in order to identify the most promising combinations of biomass resources and technologies. The project activities are shown in Figure 1 and the consortium in Table I.

2.1 Biomass production

The four selected crops were established in large-scale fields in Central Greece (by CRES), Italy (by UNIBO) and Spain (by UPM) (Fig 1). In each country one crop was established in large scale (Table II).

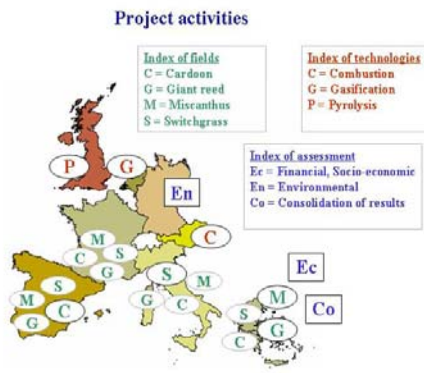

Figure 1: The project activities

Table I: The consortium and their involvement

Partners		Involvement
CRES	Greece	Biomass production
UPM	Spain	"
UNIBO	Italy	"
INRA	France	"
ASTON	UK	Pyrolysis tests
VT-TUG	Austria	Combustion tests
BTG	Netherlands	Gasification tests
AUA	Greece	Economic assessment
IFEU	Germany	Environmental
IUS	Germany	assessment

These plantations were managed using commercial available machinery. Irrigation and fertilisation were applied soon after establishment, according to the crop-specific requirements and the local soil-climatic conditions. For crop harvesting common agricultural machinery was also used [7] (Table II).

Table II: Layout of the large-scale fields

		Plant material		Equipment	
Crops	Location	Type	Density	Planting	Harvest
Arundo donax	Greece	rhizomes	0.9 plants m^{-2}	Semi-mechanically	Maize silage harvester
Cynara cardunculus	Spain	seeds	1.5 plants m^{-2}	Grain driller	Combine harvester + mower + rower + rotobaler
Miscanthus x giganteus	Greece	rhizomes	0.9 plants m^{-2}	Semi-mechanically	Maize silage harvester
Panicum virgatum	Italy	seeds	80-150 plants m^{-2}	Grain driller	Mower + baler

Apart from the large fields, all four perennial crops have been established in small-scale field trials in Greece, Italy, France and Spain, covering a total area of about 1 ha in each country. Growing techniques like irrigation, nitrogen fertilization, weed control and plant densities were studied in these small fields in order to quantify their effect on growth and yields.

The successive harvesting periods are feasible because -in contrast to the northern EU countries- under South European conditions the end of growing cycle of these crops occurs from summer (switchgrass) to autumn (miscanthus, giant reed) when inflorescence emerges. The crops can remain standing in the fields until end of February, beginning of March (switchgrass, miscanthus, giant reed), in order to obtain the lowest possible moisture content in the harvested material (Fig. 2). Having a wide harvesting window, a minimization of the storage time and the relative storage costs would be achieved.

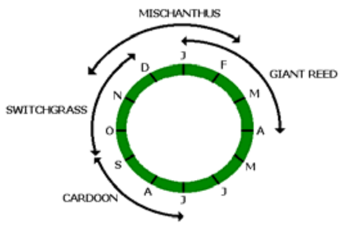

Figure 2: Harvesting window of the four selected crops

2.2 Biomass conversion

Samples of each crop from all large-scale fields were fully characterised and subjected to combustion, pyrolysis and gasification tests. Ashing was performed to ASTM-E1755-01 at a temperature of 575^{0}C. Ash fusibility tests were performed to ASTM D1857-03, whereby triangular pyramidal ash samples are heated in either an oxidising or an inert (N_2) atmosphere [3].

Combustion tests were carried out in a laboratory-scale pot reactor (50-400 gr.) and in a pilot-scale combustion unit (nominal boiler capacity 150 kWh) with larger amounts of feedstock (2-4 tons) [5]. As a reference, Austrian wood pellets were investigated with the same combustion programme.

Pyrolysis experiments were performed in a 100 g/hr bench scale fluidised bed rig [4]. Gasification tests were performed in a pilot fluidised bed gasifier (5-25 kg/hr).

For the economic analysis of the bioenergy chains BEE (Biomass Economic Evaluation) model has been used, which is a computerised model developed for this project. The model is composed of two main modules, the *cost analysis* module that performs cost estimation by activity and by input factor of biomass production, and the *financial* module, which carries out financial analysis, based on calculated future balance sheets, financial results and expected cash-flows [6].

Environmental assessment has been carried out by means of EIA (Environmental Impact Assessment) and LCA (Life Cycle Assessment). EIA was assessed as the effect of the bioenergy chains in terms of biodiversity, population, human health, fauna, flora, soil, water, air,etc. The assessment of environmental impacts of biomass production, transportation and thermochemical conversion was carried out as benefit and risk assessment. LCA of the different crops was carried out according to ISO norms 14040 to 14043. A matrix was formed including four crops, three technologies, four usage options and eight conventional types of energy.

3 RESULTS

3.1 Biomass production

Yields from the large plantations grown under practical farming conditions and harvested by available machinery as well as yields from all trials are shown in Figure 3.

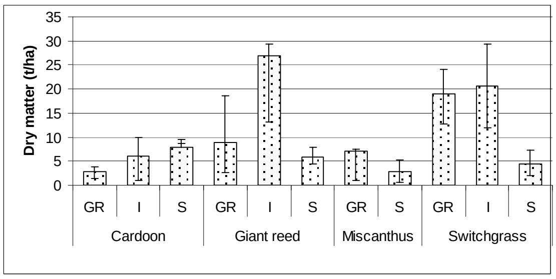

Figure 3. Yields of all crops in all sites

Yields of all crops were also measured in small trials with varying irrigation and nitrogen rates, planting densities, varieties and weed control.

There was a significant variation in dry matter yield among sites for each crop and among crops within each site. Yields were found to increase from the first to the following years. Cardoon yields ranged from 2.8 to 7.8 dt ha^{-1}, giant reed from 2.8 to 7.0 dt ha^{-1}, miscanthus from 2.8 to 7 dt ha^{-1} and switchgrass from 2.8 to 7 dt ha^{-1}

In France field trials were destroyed by adverse climatic conditions. The large variability is mainly due to the climatic conditions occurred during the three growing periods of the project. In Spain there were extreme drought conditions and since crops were not irrigated they suffered severe water stress.

Harvesting trials were conducted in switchgrass large field, focused on methods and timing, namely *summer harvesting* (including mowing, conditioning, raking and round baling) and winter harvesting (including mowing, raking and square baling). Both harvestings can be performed in South European conditions. Summer harvest is easier to carry out with machines commonly used for forage grain and allows the natural drying of the harvested material in windrows[7]. However effects on the longevity of the plantation should be considered. Winter harvesting can be carried out without mowing difficulties and big square bales can be produced when canopy is higher than 150 cm.

3.2 Fuel characterization

According to the results obtained from laboratory analysis, ash content from manually harvested biomass ranged between 5 and 6% (dry basis) for all crops, with the exception of a sample of miscanthus at 9.03%, whereas ash content of mechanically harvested biomass had a greater range and maximum values were much higher (at 22.03%) (Fig.3). The reason for the high ash content in the mechanically harvested samples is thought to be soil contamination during the harvesting process.

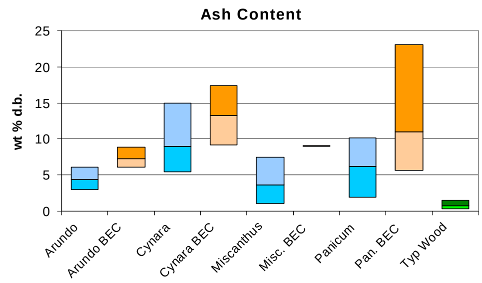

Figure 3: Ash content of the four perennial crops, compared to literature.

Note: The data from the current project (arundo BEC, Cynara BEC, Misc. BEC and Pan. BEC) are compared with literature data and data from typical wood.

Cynara cardunculus exhibited the highest ash content in comparison to the other three crops, which had similar values. Stem material contains the lowest ash content for all four crops (ranging from 2.1% for Miscanthus (< 2% for rain leached) to >5% for Cynara). The leaf material has (in general) between 2 and 4 times the ash content of the stems, with leaves collected from the ground having higher ash content due to soil contamination.

Regarding ash composition, high concentrations of Si, K, Ca, and Cl are found in all samples and characterize this type of fuels, but for cynara Na and Ca are significantly higher.

Calculated calorific values ranged from 18.3MJ/kg to 18.8MJ/kg and lie generally within the range of reported values in the literature, except for Cynara where the literature data gives HHVs in the range 16 to 18.2 MJ/kg and the stem material tested here has an HHV of c. 18.3 MJ/kg. Detailed data are reported in [3].

3.3 Combustion tests

A set of test runs at laboratory scale and in a 150 $kW_{thermal}$ KWB rotating grate furnace have been carried out on samples from all crops. Detailed data are presented in [3, 5]. At lab scale, molten ash was observed for pelletised switchgrass (ash contents 8.2 and 23%) and cardoon (ash content 17.4%) at peak temperatures of 1130 ^{0}C and 1240 ^{0}C respectively. Chopped giant reed (ash content 6.9%) and cardoon (ash content 9.2%) did not melt due largely to much lower combustion temperatures on the grate caused by bulk density and rate of heat release.

At the pilot scale switchgrass (ash content 8.3%), giant reed (ash contant 6.13%), miscanthus (ash content 2.28%) and cardoon (ash content 17%) gave severe slagging in the primary combustion zone at 1000 to 1200 ^{0}C. High K and Cl gave high concentrations of KCl in the fly ash and high rates of fouling (likelihood of severe corrosion). Increased particulate emissions were measured for all four crops. The high volume of ash generated together with accumulation of slag on the grate limited operation to ~7 hours (~ 2 hours for cardoon) before combustion performance deteriorated. Under these conditions, cardoon was not suitable for combustion purposes.

3.4 Pyrolysis tests

Fast pyrolysis tests have been performed at Aston on all four crops using a small fluidised-bed reactor at temperatures between 425 and 550 ^{0}C. Detailed data are presented in [3, 4]. For giant reed (ash content 4.2%) pyrolysis liquid yields were low due to the catalytic effect of the alkali metals. A maximum organic liquid yield of 47% on a dry ash free basis (d.a.f) was measured, this compares to values of 60 to 65% for wood feedstocks. Low oil yield was accompanied by high water content of the bio-oil and high gas and char yields. This bio-oil would be unacceptable as a fuel because of its low calorific value. Limited ash reduction by cold water washing was performed on the feedstock, reducing the ash content to 2.75% d.b (reducing K by over 55%). This led to an increase in organic liquids to 59% d.a.f.

Preliminary tests on cardoon at 444 ^{0}C (ash content of 5.7%) gave an organic liquid yield of 45% d.a.f (i.e very similar to that of untreated giant reed). Alkali metals reduction (e.g. by washing) will be essential to obtain high bio-oil yields and calorific values. Tests on switchgrass gave a high liquid yield of 71% and organic yield of 60% d.a.f and good liquid quality, comparable with wood. A high quantity of fines in feedstock was observed that led to greater char removal.

3.5 Gasification tests

Pilot scale gasification tests have been carried out by BTG on all four crops [3]. A fluidised bed gasifier was selected to permit accurate control of temperature and minimise feedstock preparation requirements (limited size reduction using hummer mill). For giant reed (which performed better that the other three crops), miscanthus and switchgrass the unit was operated without problems at temperatures of 700 to 750 ^{0}C, i.e. well below the minimum observed IDT of 1030 ^{0}C. When cardoon (ash content 13%) was tested at temperatures between 700 and 730 ^{0}C, the pressure drop of the fluidised bed increased steadily resulting in an automatic shutdown after one hour when the maximum bed pressure drop was exceeded. When the bed was inspected, large agglomerations of bed material and ash were observed. Operation at lower temperatures (<700 ^{0}C) would result in poor performance with large amounts of tar being formed. The tests on giant reed revealed much higher heating value of the produced gas and a very high tar content.

3.6. Financial/Economic Assessment

Using BEE and the collected data of the four energy crops, a primary cost analysis of energy crops production was performed. The primary result is the production cost of the four perennial crops per ton and per ha. The estimated cost is separated into two main categories: (a) cost by operation and (b) cost by factor of production.

From this analysis, cardoon resulted to be the most cost effective crop in South Europe with a production cost ranging from 28.1 to 60.0 euro/dt, according to the site (Fig 4), mainly because it is not irrigated. Costs in Italy are higher because of establishment irrigation and higher harvesting costs. Giant reed and miscanthus are the most expensive crops to grow (45.47 to 78.12 euro/dt and 42.32 to 97.24 euro/dt respectively), because planting with rhizomes is required, which is the highest cost element in biomass production. Multicropping systems are in general more costly, but elimination of lengthy storage needs, more intensive use of the agricultural equipment and the extension of plant operation may improve the economics.

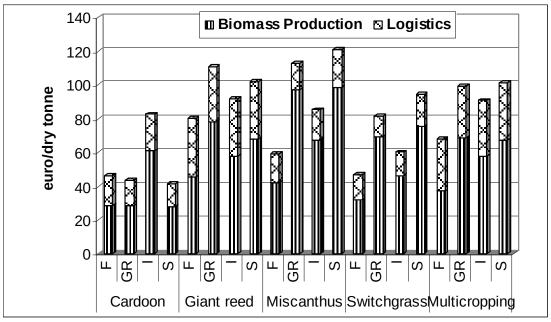

Figure 4. Cost analysis of all crops and multicropping system in all sites.

3.7 Environmental Impact Assessment

When comparing biofuels with fossil fuels, it is evident that all perennial crops contribute to non-renewable energy carriers and greenhouse gases saving and drawbacks regarding acidification, eutrofication and ozone depletion.

In terms of crop-specific assessment, it can be stated that the main disadvantage of miscanthus is the high demand for water. Cardoon is advantageous in terms of biodiversity, being indigenous in the Mediterranean flora and providing food to insects and birds. In dry areas, with sandy erosion-endangered soils, switchgrass and cardoon would be the best options, while in areas with surplus of water miscanthus and giant reed could bear very high yields. Giant reed in particular could use wastewaters being thus a crop with particular interest.

All conversion technologies have beneficial effects compared to fossil driven units, due to reduction of greenhouse emissions. Comparing biofuels and technologies among each other, a number of factors are decisive, like high crop yields, high efficiency of technologies, co-product usage in CHP plants, which increases the fossil energy saved and the fossil fuel substituted. For direct combustion and gasification, energy savings in power production are lower that in heat production due to lower efficiency during the combustion process. For heat production and combined heat/power production biomass performs best if substituting light oil and a little worse if substituting natural gas.

Variability of yields depending on the local climatic and soil conditions could affect LCA, regardless of the cropping system (with one crop or all four of them). Additionally, countries have different share of coal, oil, natural gas and nuclear power in their electric power mix, therefore, replacing different power mix by electricity from biomass may lead to different results.

6 CONCLUSIONS

The establishment, cultivation and harvesting of all four species were performed successfully using conventional agricultural methods. Yields of each crop varied considerably according to site and climate. High ash contents for all crops were measured compared to woody feedstocks and also significant variability in both ash content and ash composition. Great variability exists in biomass production costs, mainly caused by water and soil quality. Multi cropping scenarios may be more costly than single cropping systems, minimize storage and secure operation of the conversion plants. Cost of biomass production, harvesting and transportation is ~100 euro per d.t, with cardoon and switchgrass being the cheapest forms. To obtain a high environmental benefit, high, ecologically- sound crop yields should be aimed from multi cropping systems that enhance biodiversity, higher conversion efficiencies and co-products use. Energy crops should be studied at all appropriate scales and on a long-term basis to identify appropriate habitats for desired species, both for crops and lands (agricultural, managed forest and natural).

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