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TITLE: Bioenergy chains from perennial crops in South Europe

PROJECT CO-ORDINATOR:

- **Center for Renewable Energy Sources (CRESES), Greece**

PARTNERS :

- **Polytechnic University of Madrid (UPM), Spain**
- **Institut National de la Recherche Agronomique (INRA), France**
- **University of Bologna (UNIBO), Italy**
- **University of Aston, UK**
- **Institut fuer Umweltstudien (IUS), Germany**
- **Technical University of Graz (VT-TUG), Austria**
- **Biomass Technology Group (BTG), The Netherlands**
- **Agricultural University of Athens (AUA), Greece**
- **Institut fuer Energie und Umweltforschung (IFEU), Germany**

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2. Executive summary

Objectives

The overall objective of this project is to define and evaluate complete bioenergy chains from biomass production to thermochemical conversion for the production of valuable energy products. A number of perennial energy crops were 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

Description of the work performed and the achievements obtained

The four selected perennial energy crops, *Arundo donax* (giant reed), *Cynara cardunculus* (cardo), *Miscanthus x giganteus* (miscanthus) and *Panicum virgatum* (switchgrass) have been established in large-scale fields in Greece (giant reed and miscanthus), Spain (cardo) and Italy (switchgrass). Additionally, all four crops have been established in small fields in each of the four South European countries mentioned before.

Each crop was fully characterized and subjected to a comprehensive test programme of combustion, gasification and fast pyrolysis. Fuel characterization tests on feedstock samples have been completed and tests of combustion, pyrolysis and gasification at lab- and pilot scale have also been performed.

A closed access website is being set up to share all information on feedstocks and analyses between the partners.

A cost analysis and economic model, BEE (Bioenergy Economic Evaluation) has been prepared and distributed in a CD to all collaborating partners and is also hang on the internet site (www.bee.aua.gr). The cost analyses for the perennial crops were divided into three phases: a) agricultural production (cost at farm gate), b) intermediate costs (biomass treatment, transport and storage) and c) conversion costs.

The environmental characteristics of the biomass production relative to those of conventional agricultural production have been investigated by means of a questionnaire designed for this project and sent to the biomass-producing partners. Based on the data collected an input grid for all activities accomplished during plant establishment has been generated and the life cycle inventories have been compiled. The environmental impacts for accomplished life cycle steps were calculated country-specific and crop-specific.

A literature review on the state-of-the-art of all selected energy crops and thermochemical conversion technologies as well as a review on the cost models and EIA/LCA tools has been accomplished.

Exploitation Plans

The obtained results and information will be of high use for policy makers in south European countries and/or regions as well as the EU. Scientists working in this field, biomass producers, manufacturers and users of biofuels will be able to use the results to optimise processes and production chains in technical, economic and environmental terms.

The project results were distributed freely between the partners, the scientific community, the relevant European research institutes and universities, as well as the potential end-users. The dissemination of the results were performed at five different levels, entailing:

1. Publications in scientific and trade journals and presentations in international conferences, pursued by all the partners. The aim is to make the project better known to the potential users outside the consortium and to facilitate future marketing of the selected bioenergy chains (four energy cropping schemes for south EU climatic conditions, development of specific pre-treatment protocols combining perennial crops and the thermochemical conversion processes, advanced technologies – combustion, gasification, pyrolysis).
2. Dissemination of general know-how obtained during the project in seminars and workshops for industrial and academic participants on renewable energy utilization.
3. Establishment of working contacts with decision-making groups, local authorities, local agricultural and energy organisations, and technical bodies, who will promote the introduction of perennial crops for energy uses.
4. Farmers' visits in the experimental fields, where they were informed on the crop characteristics, cultivation techniques, biomass productivity, etc. and get familiar with options to diversify their cropping systems to energy cropping.
5. Establishment of a dedicated web page.

Eventually, a handbook on the specific features of the selected bioenergy chains is to be prepared in the end of the project. The handbook will include:

- Information on the selected energy cropping schemes (establishment, harvesting) for south EU climatic conditions.
- Requirements of the energy crops feedstock for the thermochemical conversion technologies under study.
- Financial/economic and environmental evaluation of the selected bioenergy schemes.

At the end of the project, a Technological Implementation Plan is submitted by all partners, indicating their intention and strategy towards dissemination and exploitation of the results obtained during the project.

3. Objectives and strategic aspects

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. Laboratory tests on the different stages of handling, pre-treating and processing these less commonly processed materials are an essential first step towards the development and the evaluation of integrated systems, particularly to compare performance on these materials with performance criteria derived from more orthodox biomass forms such as wood. Measures of product yield and product quality are particularly important.

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.

For this purpose:

- Four perennial energy crops (cardoon, giant reed, miscanthus and switchgrass) were cultivated in large fields in representative agricultural regions in Greece, Spain, France and Italy and successively harvested. Field measurements were used for the technical, economic and environmental analyses.
- Each crop was fully characterised and subjected to a comprehensive test programme of combustion, gasification and fast pyrolysis. A report on the technical evaluation of the overall integrated bio-energy chain performance from biomass in the field to a derived heat and/or power product is produced.
- A financial/economic assessment was carried out on the data collected from the previous work packages. The overall performance from biomass in the field to a delivered energy product as heat and/or power was measured by reference to the component parts in the chain starting in the field and progressing through each stage of handling and processing. An overall performance model was derived to provide consistent comparison between different bio-energy chains.
- This model was complemented with an environmental assessment also conducted in all stages of the bioenergy chains. A list of the best options, of a combination of biofuels and technology, in terms of economic and environmental benefits, for each country were produced.

The project has conformity with the following Community policies:

- Emissions of greenhouse gases: The European Climate Change Programme, launched in 2000, will primarily deal with the policies and measures to reduce greenhouse gas emissions. Energy crops can help fulfil the policy for biomass utilisation, and the perennial crops have the additional feature of increasing carbon storage in soil compared to annual cropping
- The White paper for Energy (November 1997), which reports the need to increase the contribution of biomass to the Community's energy balance. In particular, by 2010 annual energy production from biomass should increase by 90 Mtoe, whereas 45 Mtoe refer to energy crops. The main energy crop volume is anticipated to be solid lignocellulosic crops for combustion or gasification.
- The diversification and security of sustainable energy supply policy, based more and more on renewables and on lower energy intensities. The project concerns utilization of selected perennial energy crops, which could be sustainably developed in the future in rural areas of Southern Europe. In addition multifueled tests of combustion, pyrolysis and gasification will be performed with feedstock deriving from four perennial crops, that will contribute to security of raw material supply to the energy plant. A fuel flexible system will ensure an increased amount of independence regarding the choice of fuel and its distribution. It is also worthwhile to mention that the selected thermochemical processes concern the most advanced energy technologies that exhibit high efficiencies and low emissions.
- The reform of the Common Agricultural Policy, which enhances diversification in the agricultural markets of EU with the development of the proposed multicropping system with four selected perennial energy (non-food) crops, thus prevailing threats of food surpluses and detrimental effects on employment, and therefore helping the substitution of fossil fuels with biofuels. Growing biomass on excess agricultural land offers the prospect of providing farmers good incomes without the need for permanent agricultural subsidies.
- To reach the objective of doubling the renewable energy's share by 2010, energy crops will be strongly taken into account. 27Mtoe out of 45Mtoe will be produced by solid cellulosic bioenergy crops. At yields of 20-30 tonnes per hectare and year achieved when growing the four proposed energy crops under South European conditions, the production of 27Mtoe of solid biomass would imply a cultivated area of 2.7 Million hectares of land.

4. Scientific and Technical Approach

To achieve the objectives, the work has been divided in five work packages:

WP1 addresses the whole biomass production chain of the selected perennial crops under South European conditions. The selected biomass crops - *Cynara cardunculus* (cardo), *Panicum virgatum* (switchgrass), *Miscanthus x giganteus* (miscanthus) and *Arundo donax* (giant reed) - were cultivated in large fields in representative agricultural regions in Greece, Italy and Spain and field measurements were used for the technical, economic and environmental analyses in the following work packages. The establishment, cultivation (Task 1.1), harvesting and pre-treatment (Task 1.2) of the crops were carried out with conventional agricultural equipment and techniques according to the crop specific requirements.

WP2 dealt with the thermochemical conversion processes, covering fuels characterization (Task 2.1) and multifueled tests of combustion (Task 2.2), pyrolysis (Task 2.3) and gasification (Task 2.4) of the raw material produced in WP1.

A financial and economic assessment of the data collected from all previously mentioned work packages were accomplished in **WP3**. The process performance measures derived in WP2 were used to estimate overall process capital and product costs. A consistent basis was used to ensure comparability and enable economic and technical comparisons to be made. A methodology for providing overall assessment of the alternative processes was used that properly considers technical performance, economic performance, technical and financial risk, environmental factors and development requirements in order to derive recommendations for implementation.

The aforementioned financial and economic assessment were complemented in **WP4** with an environmental assessment using environmental impact assessment (EIA) and life cycle assessment (LCA) techniques were conducted in all stages of all bioenergy chains. This first step (Task 4.1) included i) an assessment to evaluate the local environmental impacts due to the production of the energy crops by using EIA and ii) an assessment of the environmental implications of the biofuels under concern compared to their fossil counterparts using LCA according to the ISO 14040/43 standards. Herewith the complete life cycles of all fuels were taken into account. Second step (Task 4.2) was a detailed assessment of all dependencies and sensitivities using results from the other work packages. Multi-functional dependencies were used to describe all differences under concern: different farming methods, country specific conditions, different technologies, different use of by-products and others. In the last Task (Task 4.3) of this Work Package, the best options for the production and use of a set of different biofuels in the future were identified using a multi-functional assessment tool. This was done for each country and region where applicable. The best options must ensure a year round availability by having lowest costs and the best environmental benefits possible.

Finally, a **WP5** detailed the coordination of the project, dealing with managerial, exploitation and dissemination activities of the consortium. A best practice manual was drawn compiling the best options of bioenergy resources and technologies in Southern European countries, in monetary, economic and environmental terms.

4.1. Biomass production (WP1)

Partners involved: CRES (Greece), UPM (Spain), UNIBO (Italy) and INRA (France)

Task 1.1 Crops establishment and cultivation

The four selected crops were established in large-scale fields in Central Greece (by **CRES**), Italy (by **UNIBO**) and Spain (by **UPM**). In order to avoid quadruplicating of the work and the associated costs, each partner was responsible for the establishment and cultivation of one main perennial crop (except CRES which was responsible for *Arundo* and *Miscanthus*), for which he has adequate previous experience (through his co-ordination/participation in previous EU or national RTD projects) and the necessary conventional equipment for mechanised cultivation (**Figure 4.1**).

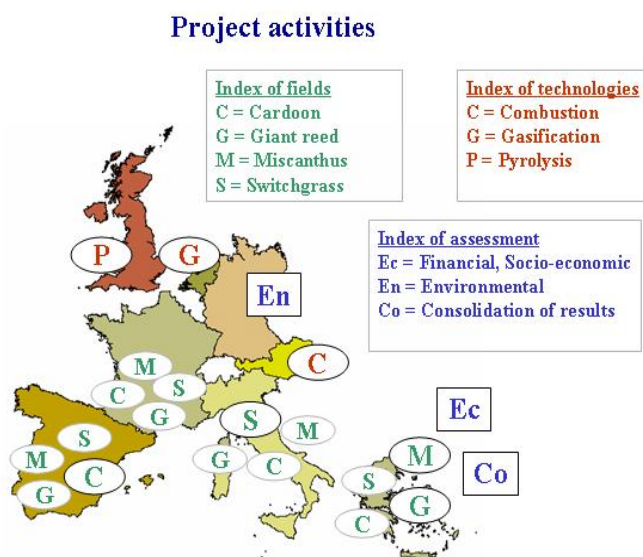


Figure 4.1: The project activities

The planting material used was:

- for *cynara*, seeds from a seed selection of UPM
- for *switchgrass*, seeds of variety Alamo, provided by UNIBO
- for *miscanthus*, rhizomes of the *Miscanthus x giganteus* hybrid were extracted from an old CRES plantation
- for *giant reed*, rhizomes were extracted from a wild-grown plantation in Greece, provided by CRES

These plantations were established using commercially available machinery. Sowing of cardoon and switchgrass was performed by common sowing machinery, while, in the case of rhizomes, they were planted semi-manually. Rhizomes were extracted by a three-ploughshare plough and cut in smaller pieces by a chain saw. Then workers seated on a track that was moving along the planting rows planted them manually (**Photo 4.1**).

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 (**Table 4.1**).

Table 4.1: Layout of the large-scale fields

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



Photo 4.1: Rhizome extracting – cutting in smaller pieces and planting

Apart from the large fields, all four perennial crops have been established manually in small-scale field trials in Greece, Italy, France (*INRA*) and Spain, covering a total area of about 1-2 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.

Task 1.2 Harvesting

The four selected crops were harvested successively. The successive harvesting periods in SE countries is feasible because - in contrast to the northern EU countries - under South European conditions the end of growing cycle of these crops occurs from summer (cynara) to autumn (switchgrass, miscanthus, giant reed) when inflorescence emerges. Progressive leaf senescence and a simultaneous dying back of the stems

follow the emergence of the inflorescence. The crops can remain standing in the fields until the end of February, beginning of March (switchgrass, miscanthus, giant reed), in order to obtain the lowest possible moisture content in the harvested material. Having a wide harvesting window, a minimization of the storage time and the relative storage costs, along with better allocation in time of the harvesting equipment use, would be achieved. The harvesting cycle is depicted in **Figure 4.2**.

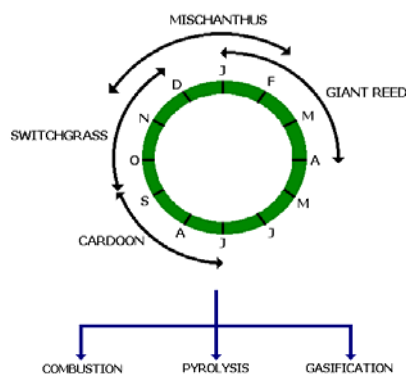


Figure 4.2 Year round availability of biomass

Cynara cardunculus (cardoon) was harvested in August-September every year. The machinery used for this purpose was: i) a combine harvester with a specially designed pickup to separately harvest the seeds, ii) a mower to cut the remained above ground biomass into pieces, iii) a rower to swath the biomass cut and iv) a rotobaler adapted for baling cardoon biomass (**Photo 4.2**).



Photo 4.2 Harvesting of *Cynara cardunculus*

Panicum virgatum (switchgrass) was harvested in November-February, while additional early harvesting trials were carried out in August, in order to compare yields and avoid soil contamination in the harvested material, though an early harvest could decrease the productive life of the plantation and the vigor of the following year's growth. Harvesting was performed by a mower which cut the above ground biomass into pieces, then raking and windrowing followed and finally a rotobaler baled switchgrass into round and square bales (**Photo 4.3**).



Photo 4.3 Harvesting of *Panicum virgatum*

Three different balers were tested in terms of bulk density reduction and profitability. Accordingly, three different kinds of bales were produced, round soft bales (RSB) with 114 kg^{-3} bulk density, round durum bales (RDB) with 153 kg^{-3} and square bales (SB) with 175 kg^{-3} bulk densities.

Harvesting of the *Arundo donax* large field was carried out in February by means of a six rows CLAAS Jaquar 690cl mower-fodder-loader combining machine (**Photo 4.4**). The efficiency of this machine was quite high indicating that it should be regarded suitable for *Arundo* harvesting. No problems were faced at all during the harvest and losses of the harvested material were low.



Photo 4.4 Harvesting of *Arundo donax* and *Miscanthus x giganteus*

Miscanthus sinensis. Harvesting was conducted in March every year (late in the season) when climatic conditions were suitable for this work. But at this time the main part of biomass was lost by storm and wind events. For the harvesting a CLAAS Jaquar 690cl mower-fodder-loader combining machine with 4 rows was used. Harvesting process was carried out without any problem.

Feedstock pre-treatment requirements (drying, sizing) were identified in the course of the project, for each crop and process technology and common protocols were introduced per technology, so that the feedstock would meet the requirements of each thermochemical conversion process.

To clarify further and optimise harvesting process of the four perennial crops in order to better meet the conversion requirements, a workshop on harvesting was held in Athens, in the Mid-term meeting of the project, where representatives of CLAAS Company were invited to present their experience on harvesting perennial grasses.

Furthermore, a literature review was carried out for each of the selected crops, in order to describe the current state-of-the-art for these crops, and compare literature data with data collected in this project.

4.2 Biomass conversion (WP2)

Partners involved: VT-TUG (Austria), ASTON (UK), BTG (The Netherlands) and CRES (Greece)

Task 2.1 Fuel characterisation

Samples from all harvests of each crop (from small and large fields) were submitted to fuel characterisation tests at CRES, VT-TUG and ASTON laboratories (**Photo 4.5**).



The scope of Task 2.1 was to gain detailed information about the characteristics of the selected perennial crops, by means of chemical analysis on fuel samples provided by CRES, UPM and UNIBO. Based on this characterisation, conclusions concerning the behaviour of these crops during their thermochemical conversion were drawn.

Photo 4.5 Fuel samples

The following characteristics have been investigated:

- Heating value
- Ash content
- Chemical composition
- Concentrations of main elements (C, H, N, S, Cl, Si, Ca, Mg, K, Na, P, Al)
- Concentrations of heavy metals (Fe, Mn, Cu, Zn, Ni, Cr, Pb, Cd, Hg)

Ashing was performed to ASTM-E1755-01 at a temperature of 575⁰C. Ash fusibility tests were performed to ASTM D1857-03, whereby triangular pyramidal ash samples are heated in either an oxidising or an inert (N₂) atmosphere.

In addition to the wet chemical analyses, a literature review on relevant fuel analyses of the selected crops was performed and literature data were summarised in a database. The results of the analyses performed were then compared with the literature data as well as with fuel wood chips and wheat straw data.

BTG analysed the ash melt behaviour of the selected crops. The behaviour of the ash derived from biomass can be a critical factor in all thermochemical conversion processes. An ash that fuses easily into a viscous liquid can form clinkers in the reactor or block the system. Additionally, part of the inorganics may appear in the gas phase causing an emission problem. The behaviour of ash under reactor conditions will strongly influence the selection of a conversion technology.

For the analysis of the ash melting behaviour the standard Seger cone method (ASTM D2013 – D3174) had been used. Ash melting tests have been performed in air and in nitrogen atmosphere (inert). With the current set-up it was not allowed (for safety reasons) to use a reducing atmosphere.

Laboratory analysis of samples from all final harvests of each crop (from small and large fields) was conducted in CRES laboratory for feedstock characterisation.

- Proximate analysis to determine moisture, volatile, ash and fixed carbon content, using a thermogravimetric analyzer.
- Gross calorific value using an oxygen bomb calorimeter.
- Hydrogen, carbon and nitrogen content, by a microprocessor controlled elemental analyser.

Feedstock of each crop grown in the large fields was sent to ASTON, VT-TUG and BTG for the performance of the combustion, pyrolysis and gasification tests, as shown in the **Figure 4.1**.

Task 2.2 Combustion tests (VT-TUG)

The aim of this task was to perform combustion test runs at a laboratory-scale fixed-bed reactor as well as in a pilot-scale fixed-bed combustion plant.

At the laboratory-scale fixed-bed reactor test basic information about the behaviour of these fuels during combustion was gained by the investigation of the ash melting in the fuel bed, the release of certain species causing NO_x emissions and the influence of the fuel preparation applied (chopped or pelletised materials).

The investigations at the pilot-scale plant were focused on the identification of possible operational problems such as fuel feeding, ash melting on the grate and in the furnace, ash transport systems, emissions (NO_x, SO_x, HCl and particulates), formation and growth of deposits (fouling tendencies), fractionation of elements in the different ash fractions.

Fuels for the test runs were provided by CRES (miscanthus and giant reed), UNIBO (switchgrass) and UPM (cardoon). Most of the fuels were tested as received in order to get an as realistic as possible fuel, while the chopped material (miscanthus and giant reed) were additionally pelletised for the lab-scale test runs.

Test runs were performed at a laboratory-scale reactor at TUG as well as at a 150 kW_{th} pilot-scale combustion plant at the company KWB – Kraft und Wärme aus

Biomasse GMBH in Austria, which has been specially designed for the combustion of solid biomass fuels with high moisture and high ash contents (**Photo 4.6**).

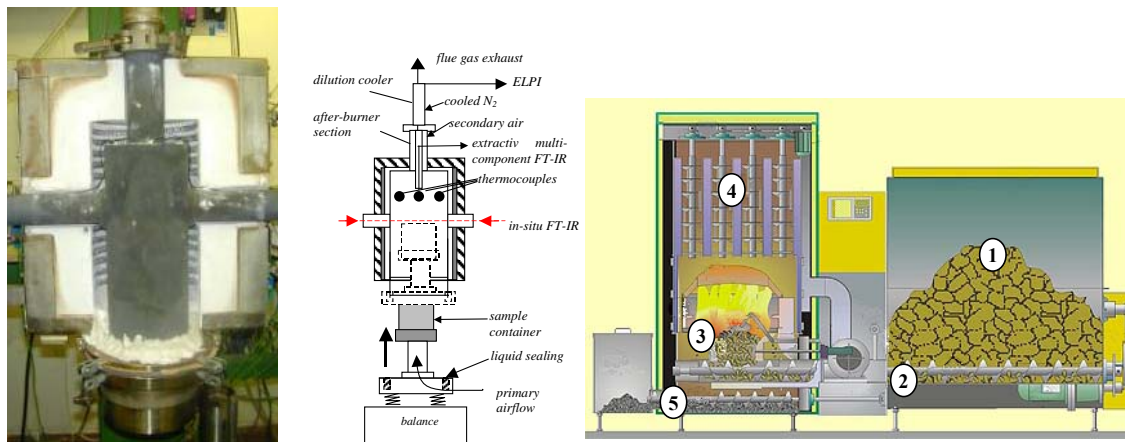


Photo 4.6 From the left to the right, the laboratory-scale reactor at TUG and the 150 kWth pilot-scale combustion plant at the company KWB.

Task 2.3 Pyrolysis tests (ASTON)

Pyrolysis experiments were performed in a 100 g/hr bench-scale fluidized bed rig (**Photo 4.7**).

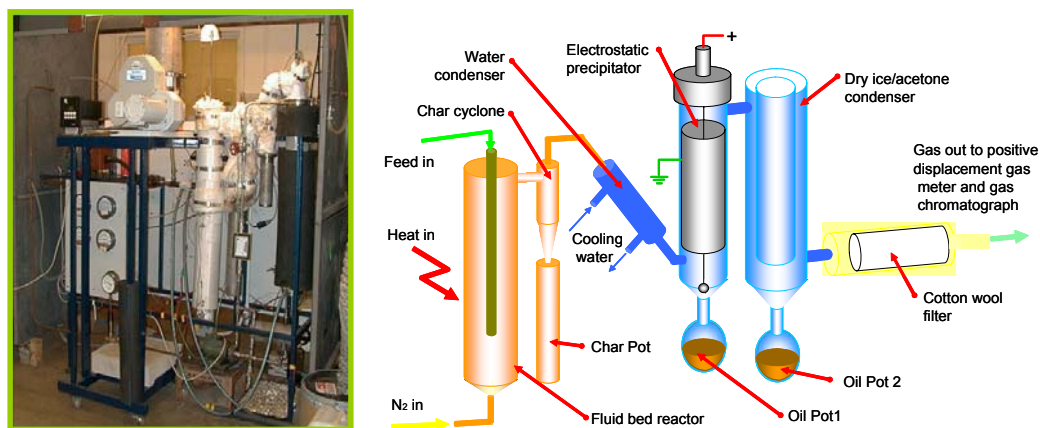


Photo 4.7. Aston 100 g/h fluidised bed fast pyrolysis unit

Materials from all crops were pyrolysed under a range of conditions as defined below:

Feed material: Water content from as received down to 5%,

Temperature: A range of pyrolysis temperatures were studied from 450 °C to 550 °C in 25 °C steps to derive the temperature for maximizing liquid yield and the temperature for optimizing liquid quality

Liquid Product: The following data will be Mass balance; energy balance; liquid product yield, viscosity, water content, stability, heating value, density were derived for each experimental run.

The laboratory scale testing was performed on a small laboratory fluidized bed pyrolyser. Selected materials were tested on a small pilot plant (10kg/h) based at Aston to investigate the effect of scale.

Task 2.4 Gasification tests (BTG)

In this project a fluidised bed reactor has been selected as gasifier. For the energy crops under consideration, the feeding system requires special attention. Due to the low bulk density of the material was expected not flow freely and the risk of bridging would be significant. Also, the actual feeding rate might be lower than e.g. wood chips. A fluidised bed gasifier is sensitive to irregular feeding, therefore, at the start of the project it has been considered to test the feeding system separately, and modify it, if required, prior to the actual gasification tests.

Gasification tests were performed by BTG in a laboratory-scale and a pilot fluidised bed gasifier (5-25 kg/hr), located in Enschede (The Netherlands) (**Photo 4.8**).

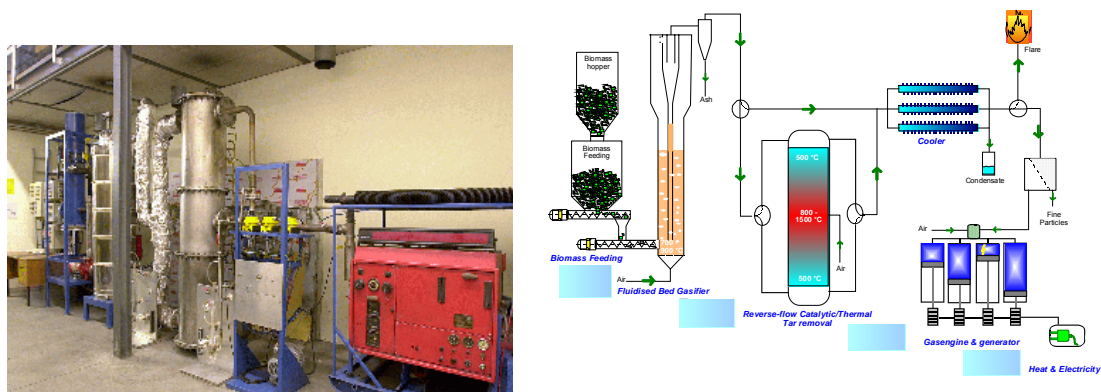


Photo 4.8. A pilot fluidised bed gasifier (5-25 kg/hr) at BTG

Extensive experimental daily tests were carried out, for the different types of biomass selected according to international standards. This includes the gas composition of main constituents (up to C3), tar and dust content in the product gas, amount of ash production, carbon content in the ashes and gasifier efficiency. Tests were conducted at varying conditions, i.e. at different load levels and different fuel moisture content. In this way, the suitability of the crops for gasification at varying conditions can be determined.

4.3 Financial/Economic analysis (WP3)

Partners involved: AUA (Greece) and ASTON (UK)

The main objective of this part of the work was the overall economic assessment of various selected chains of bioenergy production. This analysis covers all stages from agricultural production to useful final fuel.

Analytically:

- Agricultural Production (monoculture of multi-cropping systems)
- Harvesting (three scale scenarios)
- Storage (three scale scenarios)
- Transport (three scale scenarios)
- Biomass Conversion (Combustion, Gasification, Pyrolysis)

4.3.1 Agricultural Production

The economic evaluation of agricultural production is tracing all costs incurred in the field, by agricultural activity of energy crops. In general, agricultural production differs from industrial activity. Here, a more business like approach is adopted and a compromise between agricultural accounts and financial reporting, in order to be able to consistently consolidate agricultural and industrial (biomass conversion) activities. The economic analysis of biomass production has been greatly assisted and standardised by the Bioenergy Economic Evaluation (BEE) computerised model, which was developed within the project for this purpose.

The economic analysis of agricultural production covers all cultural practises before biomass harvesting. For this analysis two basic scenarios were made. The first scenario covers the production of every crop as a monoculture. The result of this analysis is the cost of production for every crop in each country (i) per cultivated hectare and per tonne, (ii) per agricultural operation and per production factor/input. This part also covers the economic comparison between energy and selected conventional crops that estimates for each case the break even price of energy crops, that makes their production economically viable for the farmer.

The second scenario covers the joint production of (i) all four crops and (ii) a mixture of Arundo, Miscanthus and Switchgrass. The cultivation of more than one crop is in general more costly. However, due to reduction of storage needs, possible increase in the use of agricultural equipment and more efficient operation of the transformation plant during the year, it may be preferable in some cases.

4.3.2 Harvesting, Storage and Transport analysis

Energy crops can be harvested and transported in different ways and forms. For this study five forms were considered: a) Pellets, b) Bundles, c) Bales, d) Billets and e) Chips. Economic analysis of harvesting storage and transport was performed for every crop and every form in each country. The most cost effective form was selected for more detailed analysis.

Due to economies of scale, three basic scales were analysed:

- Small scale: 4,000 tonnes of dry biomass for 3 km average distance
- Medium scale: 15,000 tonnes of dry biomass for 6 km average distance
- Large scale: 50,000 tonnes of dry biomass for 10 km average distance

Equal quantities of each crop in each case were assumed.

This analysis was also performed for (i) single crop and (ii) combination of crops, as mentioned before.

4.4 Environmental analysis (WP4)

Partners involved: IUS (Germany), IFEU (Germany) and INRA (France)

Bioenergy is regarded to be environmentally friendly. But is this true? This was verified in WP 4 “Environmental assessment”. The two partners IFEU and IUS had different tasks that were on the whole independent of each other. IFEU carried out the life cycle assessment (LCA), whereas IUS executed an environmental impact assessment (EIA).

4.1 Life Cycle Assessment (IFEU)

The aim of the study was to compare the environmental impacts of the different bioenergy chains of perennial crops with respect to their fossil alternatives and among each other, considering their life cycles from the growing region and agriculture to conversion and usage.

From the different crops, all possible life cycles were compared regarding their environmental impacts. Four crops, three ways of conversion, three usage options, and seven conventional energy technologies replaced lead to a number of 60 basic balances and 1672 sensitivity analyses being calculated. These calculations took all single processes into account, from the extraction of raw materials to different utilization options and co-products (“cradle-to-grave approach”). In doing so, different boundary conditions were considered concerning climate, efficiency, and co-products of the conversion processes, production expenditures for the machinery as well as the national infrastructure of the country of crop cultivation.

In detail, this investigation compared the four bioenergy crops *Arundo donax* (giant reed), *Cynara cardunculus L.* (cardo), *Miscanthus × giganteus*, and *Panicum virgatum* (switchgrass), partly after gasification and pyrolysis, in production of heat, electricity, and combined heat/power (CHP) with their conventional equivalents. As we presumed that relatively small plants of some megawatt at maximum are built for the comparison the following conventional technologies were considered: heat from natural gas and light oil, electricity from the grid in different countries, and CHP from natural gas and light oil, respectively.

The assessment of the environmental impacts of the different crops using LCA was carried out as indicated in principle by the ISO norms 14040 to 14043 (ISO 1997-2000). All boundary conditions and definitions concerning the goal and the scope of the LCA have been determined and are correspondingly documented in Borcken et al. (1999) as well as in IFEU (2000).

4.2 IUS – Environmental impact assessment

Environmental impact assessment is a procedure for examining proposed activities early in planning for their potential to impact the environment. The aim of environmental impact assessment is to identify, describe and assess the effects of a project on environmental issues. In general, EIA is working on a site specific level,

i.e. environmental effects of projects are investigated on the basis of detailed analysis of different environmental factors, e.g. soil or vegetation at a certain site.

The assessment of environmental impacts of biomass production, transportation and thermochemical conversion is carried out as benefit and risk assessment, i.e. without explicit knowledge of possible sites for biomass production and thermochemical conversion in the future.

The first step of the EIA is the crop-specific assessment of the four energy crops of concern in this study. On this basis, an investigation of crop-specific differences is carried out. An evaluation of the energy crops relative to the reference systems “natural land” and “annual row crops” is done by qualitative-descriptive classification in 5 classes.

Benefit and risk assessment for thermochemical conversion and transportation is based on the investigation of potential effects of biomass conversion units compared to fossil driven units (effects on climate) and different conversion technologies compared against each other (effects on human health, soil, flora, fauna and landscape). Effects on climate are derived from results of LCA.

5. Scientific and Technical performance

5.1 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 5.1**.

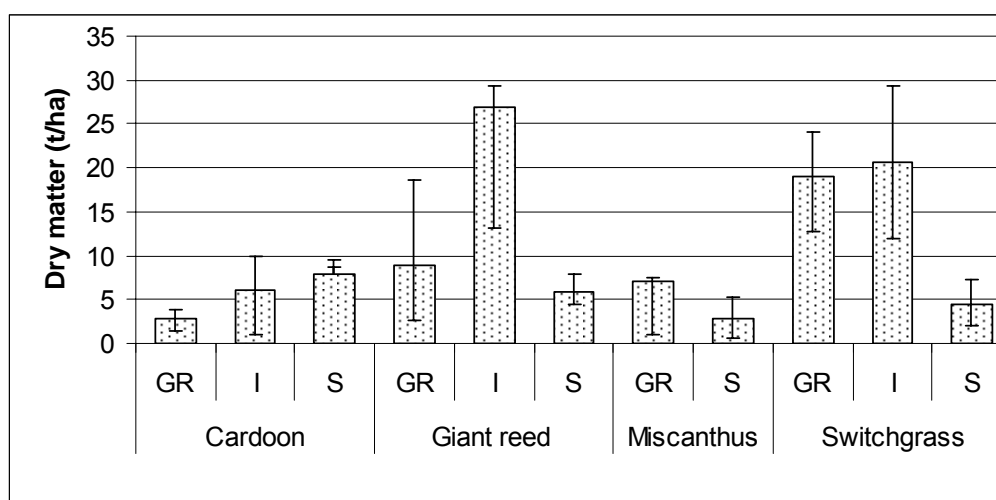


Figure 5.1. Yields of all crops in all sites

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.

Analytically:

In Greece:

All crops were in the second – third growing period, therefore the yields presented are not considered as mature yields. The irrigation treatments had a more pronounced effect on the recorded characteristics than nitrogen fertilization. Nitrogen fertilization affected significantly several growth and yield characteristics but mainly in irrigated plants indicating that both irrigation and nitrogen fertilization are important for achieving high yields.

Regarding giant reed, a slight increase in biomass yields was noticed between the first and the second growing periods. Yields in the third growing period almost doubled. However the maximum values recorded differ considerably from the expected values based on our experience on giant reed. It could be attributed to the low planting density, which resulted in low plantation density. In the case of switchgrass the dry matter yields of the second and third growing periods were of the same range. Cardoon yields were much lower than the yields achieved in previous field trials in Greece. This was due to the frost that damaged the plantation in its second growing cycle. Also, the nitrogen fertilisation effect was impossible to be revealed.

Regarding the multicropping system, it is anticipated that yields of at least 15 t ha⁻¹ dry matter could be harvested by cardoon from July until September. Switchgrass, when harvested in November until February can produce yields ranging from 12 t ha⁻¹ to 22 t ha⁻¹ dry matter. Then, in February to March giant reed can be harvested with yields ranging from 8 to 18 t ha⁻¹, closing thus a harvesting window of nine months a year.

The harvesting of giant reed and miscanthus can be carried out by the usual agricultural machinery – a maize harvester.

In Spain:

The results of this work show that in the experiment conditions (central Spain, Haploxeralf Calcic soil, xeric Mediterranean climate) the crop that exhibited best performance and higher yields was cynara, in spite of the fact that it was the only non-irrigated crop. The three-year mean of the yields obtained for miscanthus, switchgrass, arundo and cynara were equivalent to 2.8, 4.4, 5.8 and 7.8 t dry matter ha⁻¹, respectively.

The results showed that cynara –after the establishment- is a very hardy crop, resistant to water stress. The third crop cycle was extremely dry; the total precipitation was only 228 mm (Sept/04-Aug/05). Cynara overcame that severe drought, endured unfavourable soil conditions and produced nearly 6 t dm ha⁻¹.

The trials of mechanical harvesting of cynara with existing conventional machinery showed that specific machinery should be developed. At the field level, the most important issues are the optimization of the harvesting efficiency and the separation of the oil seeds from the lignocellulosic biomass in a clean way, without soil contamination. For the purpose of biomass combustion the most important issue is the

fact that the way in which the harvest is accomplished affects the biomass quality. Further studies are needed to undertake the development of specific machinery.

Arundo -grown with irrigation- was second in performance in this experiment conditions. However, the plant density was too sparse for a three-year experiment. If the plant spacing had been thicker (<1.5 m between rows) the final yields would have been better. Miscanthus and switchgrass performed badly; the effect of the harsh experimental conditions on the plant growth was notable since the establishment of the crops.

In Italy:

The three perennial crops confirmed to be well adapted to this environment. They also appeared very tolerant to drought and diseases. Still, the yield was not significantly affected by nitrogen rates, hence their cultivation may be supposed to be very sustainable and economic.

Cardoon produced a consistent lower dry matter yield than the two other crops. However it also showed a very shorter cycle and then it reached its maximum yield very earlier than the other two crops with a dry matter content of biomass of about 80%. This may be positive as it accelerates the baling process. Furthermore it allows to harvest and deliver biomass to the plant during summertime thus to integrate the other two crops according to the project thinking.

Arundo showed an higher potential yield than switchgrass, however the later is propagated by seeds (instead of rhizomes) and it is likely much easier to mechanize both during plantation and harvest. In this research conventional harvesting machines were found to perform very well on switchgrass, while some problems occurred with arundo because of the too long stems. The only problems we encountered with switchgrass concerned the baling operation with soft core baler machines which did not work appropriately with stems longer than 1.80 m.

Because of seed propagation, switchgrass appears currently much more economic than arundo. For instance, in Italy the plantation cost of arundo (genetic material only) is about 10.000 € ha⁻¹, while that of switchgrass is lower than 100 € ha⁻¹.

Lowland ecotypes of switchgrass were found to be significantly more productive than upland varieties. However, upland types showed a very short cycle with a marked attitude in re-growing after the summertime cut (though rainfall is needed). Thus a possible attractive hypothesis could be to cultivate upland varieties with a double cut per year. This would reduce the risks of a winter harvest and storing, while simplifying the field operation and allowing to deliver half biomass to the plant in summertime and the other half in wintertime.

In France:

Cardoon, giant reed, switchgrass and miscanthus were re-established in March 2003 in South France. However, due to adverse climatic conditions that prevailed in summer 2003, the fields were destroyed. Consequently, cardoon was re-sown in October 2003 and giant reed was replanted in December 2003. Miscanthus and switchgrass were reestablished in spring 2004.

The yield of *Miscanthus* was very variable. The maximum value of more than 30 tones of dry matter per hectare shows the high potential of this crop.

The yield of *Arundo* was much lower and we should think that after one year and a half the establishment is not finished.

The yield of *Switchgrass* was very constant near 15 tones of dry matter per hectare.

The lack of data obtained is a result, as it shows a critical point which is the implantation phase.

Miscanthus and *Arundo* are rhizomatous plants. The problem of there implantation is the high cost due to the lack of mechanical tool. To cultivate these two plants at a larger scale, it seems important to work on rhizomatous planting machine.

With the productivity data collected in Estrées-Mons, we shown that the potential production of the three crops, *Arundo donax*, *Miscanthus x giganteus*, and *Panicum virgatum*, is very high. For its part, *Cynara cardunculus* seems less adapted to French conditions.

Nevertheless results shown that: (i) variability is important (except for *Panicum*) and may be due to implantation problems. (ii) *Arundo* seemed to require more time than *Miscanthus* to reach an optimum production.

5.2. Biomass conversion

Partners involved: VT-TUG (Austria), ASTON (UK), BTG (The Netherlands) and CRES (Greece)

5.2.1 Fuel characterisation

In **Table 5.1** the results of the wet chemical analyses of the 18 fuel samples are summarised.

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. 5.2**). The reason for the high ash content in the mechanically harvested samples is thought to be soil contamination during the harvesting process

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.

Table 5.1: Analyses results of samples investigated within the project

Sample	ash	C	H	N	GCV*	GCV**	Cl	S	K	Na	Ca	Si	Mg	Al	P	Fe	Mn	Cu	Zn	Ni	Cr	Pb	Cd	Hg
	[wt% d.b.]					[kJ/kg d.b.]																		[mg/kg d.b.]
Aru-CRES-3_2003-c	6.9	45.4	5.6	1.1	18,640	18,029	2,180	2,605	6,641	171	2,450	10,884	1,325	481	1,187	451	65	8.8	38	2.8	4.5	1.6	0.3	<0.05
Pan-BOL-2_2003-c	6.9	45.0	5.3	0.8	18,250	17,428	1,615	1,208	3,808	202	5,412	11,574	1,474	815	1,617	561	56	4.2	50	1.7	2.4	1.4	0.1	<0.05
Mis-UPM-5_2003-m	9.0	n.a.	n.a.	n.a.	n.a.	n.a.	756	542	1,731	45	5,018	27,349	759	1,011	259	534	147	3.9	45	4.2	9.3	9.6	0.1	n.a.
Aru-UPM-5_2003-m	6.0	n.a.	n.a.	n.a.	n.a.	n.a.	5,410	2,660	10,545	72	2,349	9,852	1,289	217	946	127	71	4.5	24	2.1	3.7	2.8	0.03	n.a.
Pan-UPM-5_2003-m	5.7	n.a.	n.a.	n.a.	n.a.	n.a.	3,443	1,219	4,016	180	5,104	12,517	2,064	244	719	184	66	3.8	28	1.4	2.7	4.7	0.02	n.a.
Cyn-UPM-8_2001-p	17.4	40.4	5.7	1.1	16,060	16,756	17,780	1,566	21,546	10,330	19,025	21,142	3,936	4,445	1,416	2,087	45	7.7	9	9.0	6.9	9.2	<0.01	<0.05
Pan-BOL-2_2003-p	23.0	37.2	4.4	0.7	15,096	14,054	1,396	1,196	7,966	1,381	18,072	58,888	2,714	9,581	1,147	5,049	178	13.1	36	14.4	27.1	4.6	0.1	n.a.
Cyn-UPM-8_2003-c	9.2	41.9	4.3	1.2	n.a.	15,000	5,528	944	22,060	6,688	12,370	2,718	2,635	376	1,524	264	20	3.3	8	0.8	1.6	2.3	0.01	n.a.
Cyn-UPM-8_2003-w	7.2	46.7	6.2	1.9	n.a.	19,513	3,111	1,935	21,950	473	7,844	1,466	3,206	289	3,769	219	18	7.5	21	1.3	1.9	1.7	0.1	n.a.
Pan-BOL-8_2003-p	8.3	43.7	4.8	0.7	n.a.	16,283	1,511	735	12,756	924	6,555	14,991	2,223	763	1,124	1,253	55	6.5	15	3.4	6.2	1.8	0.02	n.a.
Aru-CRES-2_2004-c-I	8.9	45.0	6.0	1.6	n.a.	18,611	3,516	3,025	12,051	633	2,949	18,753	1,632	2,194	1,234	1,087	115	5.0	28	6.8	18.3	5.0	2.0	n.a.
Aru-CRES-2_2004-c-II	6.1	45.9	5.9	0.7	n.a.	18,612	2,240	2,160	6,497	331	3,253	13,920	1,627	919	781	576	38	3.3	19	3.0	3.7	3.6	0.1	n.a.
Mis-CRES-2_2004-c	2.3	47.3	6.1	0.2	n.a.	19,124	880	390	1,446	58	1,776	6,326	644	82	87	73	9	1.4	12	1.0	1.6	0.54	0.01	n.a.
Pan-BOL-2_2004-c	4.6	46.1	5.5	0.5	n.a.	18,057	3,143	603	8,507	541	2,471	9,584	1,714	100	918	99	20	2.9	16	0.7	0.4	0.2	0.0	n.a.
Aru-BOL-2_2004-c	5.7	46.7	5.3	0.6	n.a.	18,063	3,669	2,327	9,694	48	2,299	12,087	1,666	77	838	101	35	2.6	12	1.0	0.6	0.2	0.0	n.a.
Cyn-BOL-8_2004-c	8.6	46.0	5.2	0.8	n.a.	17,945	10,086	1,405	11,590	12,403	12,797	1,894	1,046	395	2,087	196	20	6.7	25	1.6	1.3	0.6	0.2	n.a.
Cyn-BOL-9_2004-c	6.6	48.2	5.5	0.9	n.a.	19,175	5,777	1,065	9,984	9,110	9,676	896	927	192	2,293	101	16	8.5	22	1.0	0.4	0.3	0.2	n.a.
Cyn-UPM-8_2003-p	20.6	38.9	5.0	1.1	n.a.	15,490	13,370	2,023	19,790	10,542	42,678	18,510	3,638	5,081	1,183	2,592	70.5	6.0	18	4.0	15.6	6.5	0.1	n.a.

Explanations: Sample nomenclature: Aru ... Giant Reed; Pan ... Switchgrass; Mis ... Miscanthus; Cyn ... Cardoon; CRES, BOL and UPM define the partner who supplied the fuel sample; the numbers indicate the harvesting time; c, m, p indicate if the sample was received as chopped, milled or pelletised material (e.g.: Aru-CRES-3_2003-c ... Giant Reed from CRES harvested in March 2003, chopped material); *...measured; **... calculated according to [Channiwala S.A., Parikh P.P., 2002: A unified correlation for estimating HHV of solid, liquid and gaseous fuels, Fuel 81 (2002), pp 1051-1063]; n.a. ... not analysed

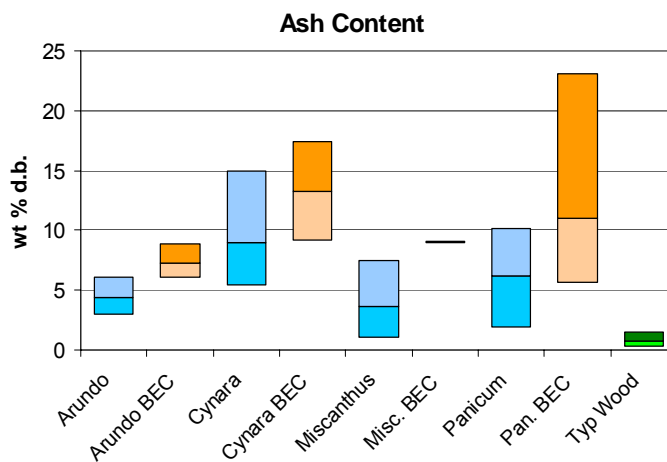


Figure 5.2: Ash content of the four perennial crops, compared to literature.

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.

5.2.2 Combustion tests

Results gained from the lab-scale test runs

Besides test runs with the crops investigated within the project also test runs with wood pellets (for comparison) as well as mixtures of Switchgrass pellets and wood pellets (to show the influence of fuel blending) have been performed. In Table 5.2 the most relevant data gained from the test runs are summarized.

Table 5.2: Results from test runs performed at the lab-scale reactor

Fuel		SG	MI	GR	CA	SGP -high ash	SGP -low ash	MIP	GRP	CAP	WP	Mix ⅓WP- ⅓SGP	Mix ⅓WP- ⅓SGP
No. of test runs		4	3	4	2	3	2	3	4	5	3	2	3
Ash content	wt% d.b.	7.0	2.3	6.1	9.2	23.0	8.3	2.3	6.1	17.4	0.5	3.0	4.1
Moisture content	wt% w.b.	6.8	10	12	5.2	6.8	9.5	9.1	9.0	6.9	7.9	7.6	8.6
Sample weight	g	39	84	55	99	436	377	429	458	336	425	416	404
Duration of test	min.	12	22	27	41	45	40	40	47	37	51	36	45
Ignition after	sec.	115	163	205	200	680	332	447	958	529	1,092	396	435
Max bed temp	°C	835	911	903	699	1,279	1,220	1,157	1,165	1,080	1,200	1,178	1,154

Explanations: SG ... Switchgrass; Mi ... Miscanthus; GR ... Giant Reed; Cyn ... Cardoon; WP ... wood pellets; P after the fuel name indicates pelletised material; all data are mean values; all test runs were performed with furnace preheating to 750°C and a primary air flow of 30 Ndm³/min; d.b. ... dry basis; w.b. ... wet basis

Generally the chopped material ignites faster and the durations of the test runs with the chopped material are generally shorter than with the pelletised material. Chopped Cardoon, which after a fast ignition has a very long charcoal combustion phase, is the only exception. The reason therefore are the hard and dense stems of Cardoon in the sample investigated.

The maximum bed temperature is the highest temperature measured by the six thermocouples placed in the fuel bed. This temperature is significantly higher for the pelletised materials compared to the chopped materials. This high temperature in the bed (about 1200°C), is probably also the reason why ash melting was only observed during test runs with the pelletised materials and not with the chopped materials (bed temperatures of 700-900°C).

Concerning the release of the NO_x-precursors the following important results have been achieved:

- Generally the pelletised fuel samples had a higher nitrogen conversion rate to TFN (total fixed nitrogen in the flue gas species) than the chopped fuel samples which is mainly due to increased formation of NH₃, whereas emissions of NO were significantly lower. This represents an important advantage for the pelletised materials due to the fact that NH₃ is an essential NO reducing agent.
- The nitrogen conversion rates to TFN are in the range between 20.6 to 35.2 wt% (chopped) and 26.9 to 42.9 wt% (pelletised). For comparison the nitrogen conversion rate to TFN for wood pellets is 21.89 wt%.
- During test runs with chopped fuels NO and NH₃ and only for Miscanthus HCN were the most important main NO_x-precursors while for pelletised fuels NH₃ followed by NO and, in the case of Miscanthus, HCN, are the most relevant NO_x-precursors.
- The mixtures of pelletised Switchgrass with wood pellets showed higher nitrogen conversion rates but due to their lower fuel nitrogen content the emissions of NO_x-precursors were in total smaller than for pure pelletised Switchgrass.

Results gained from the pilot-scale test runs

Besides test runs with the crops investigated within the project also test runs with mixtures of Switchgrass pellets and wood pellets (to show the influence of fuel

blending) have been performed. In **Table 5.3** the most relevant data gained from the test runs are summarised.

Table 5.3: Overview of test runs performed and average operational data obtained at the pilot-scale combustion plant

Fuel		SGP	GR	MI	CAP	WP**	Mix: 2/3WP- 1/3SGP	Mix: 1/2WP- 1/2SGP
Moisture content	wt% w.b.	9	22	14	11.6	8	8.7	8.9
Ash content	wt% d.b.	8.3	6.1	2.3	20.6	0.5	n.m.	n.m.
Duration	days	3	4	2	3	2	1	1
Average load***	kW	93	71	55	100	223	93	73
Ave. Prim. T.	°C	850	990	735	700	1,043	524	709
Max Prim. T.	°C	1,071	1,243	1,121	807	1,130	928	959
Ave. Sec. T.	°C	660	630	550	720	1,141	704	605
CO ₂ in the flue gas	vol% w.b.	10	8	8	9	13	12	11
H ₂ O in the flue gas	vol% w.b.	11	11	9	12	12	13	12
Emissions ****)								
Total fly ash	mg/Nm ³	58	102	27	1,319	21	22	23
Fly ash <1µm	mg/Nm ³	50	67	16	1,062	16	18	15
NO _x	mg/Nm ³	368	363	187	297	106	339	318
CO	mg/Nm ³	145	443	55	672	1	35	307
HCl	mg/Nm ³	18	67	59	162	3	23	22
SO ₂	mg/Nm ³	91	278	53	48	3	27	30

Explanations: SGP ... Switchgrass pellets; Mi ... Miscanthus; GR ... Giant Reed; CAP ... Cardoon pellets; WP ... wood pellets; **... results of test runs were performed in a previous national Austrian project; ***...boiler heat; Ave...average; Prim.T.... flue gas temperature in the primary combustion chamber; Sec. T....flue gas temperature in the secondary combustion chamber; n.m...not measured; d.b. ... dry basis]; w.b. ... wet basis; **** ... emissions related to dry flue gas and 13 vol.% O₂; Austrian limiting values for combustion plants with a nominal boiler capacity between 100 and 350 kW: NO_x: 350 mg/Nm³ (for chemically non treated wood waste) resp. 250 mg/Nm³ (for natural wood); CO: 250 mg/Nm³; dust: 150 mg/Nm³

Higher loads of the combustion unit were obtained with the pelletised fuels (SGP, CAP) compared to the chopped fuels (GR and MI) which is mainly explained by the higher energy density of the pelletised fuels. The pilot-scale test runs with wood pellets (WP) were performed prior to the test runs with the perennial crops. The combustion technology used was the same, but the nominal boiler capacity of the plant was higher (220 instead of 150 kW_{th}). Therefore, the load of the combustion plant was also significantly higher during these experiments. However, the higher energy density of wood pellets is another important factor contributing to the higher load in these test runs.

Gaseous and fly ash emissions

It was revealed that the emissions of HCl, SO₂ and NO_x formed during the combustion of perennial crops are much higher than during wood pellet combustion. The reasons for this are the higher concentrations of Cl, S and N in these fuels (see also section 2.4).

Moreover, also the amounts of dust and fine particulate (aerosol) emissions formed are significantly higher during the combustion of SGP, CAP and GR and especially during the combustion of CAP. This was also postulated from the fuel characterisation analyses which showed high concentrations of aerosol forming elements such as K and Na in these fuels. By mixing SGP with wood pellets the average emission of particles is reduced by about the ratio of the fuel mixture. The highest average concentrations of dust were measured during the test runs with Cardoon.

Compared to the current Austrian limiting values for small-scale combustion, the NO_x limiting value was exceeded during the test runs with SGP, GR and CAP. The mixing of SGP with wood pellets reduced the NO_x-emissions.

The CO limiting value was exceeded during the test runs with GR, CAP and the ½SGP/WP mixture. This is mainly due to non stable combustion conditions on the grate during some of the test runs. An important factor disturbing the combustion process was slagging on the grate which disturbs the uniform distribution of primary air through the grate and the fuel bed, and therefore increases CO-emissions.

Ash melting and slagging

Ash melting in a combustion plant can cause several problems with the operation of the plant. In the case that the ash melts on the grate (so called slagging), the fuel feeding, the ash removing from the grate as well as the primary combustion air flow through the fuel bed are disturbed. Moreover, molten ash is also much more chemically active than solid ash and can thereby also cause severe damages by corrosion of the grate and of ceramic lining of the combustion chamber. Slagging was observed within the first 12 hours of operation during all test runs with the perennial crops investigated at the pilot-scale combustion plant. The most severe slagging was observed during the test runs with the CAP, where a thick layer of slag was formed on the grate completely blocking the primary air addition through the grate after about 4 hours of operation. During the test runs with SGP slagging caused the shut down of the plant after about 7 hours of operation.

The test runs with GR and MI also showed slagging on the grate although not that severe and also not within that short operation periods such as the CAP and SGP did. However, the combustion of these fuels revealed other additional problems such as keeping a steady fuel feed and constant high fuel load on the grate. These problems are due to the low density of these fuels. In order to keep high and constant fuel loads, large volumes of fuel had to be added to the combustion chamber which after a while became overloaded with fuel and ash. The first shut down during the tests with these fuels was therefore not only due to slagging, but mainly the results of an overfilled primary combustion chamber. To avoid this problem, the design of a combustion chamber with a higher volume than usually used for wood combustion would be an appropriate measure.

Moreover, the test runs with the mixture of SGP and wood pellets revealed a significant improvement in terms of slagging in the case of the ½ WP and 1/3 SGP mixture. Molten ash was still found in the bottom ash but no molten ash “cake” was formed on the grate. In this case the cake was broken into smaller pieces and could thereby be transported from grate by the automatic ash removing system. During the test run with ½ SGP and ½ WP again an ash layer “cake” was formed on the grate,

although not as thick as during the test runs with 100% SGP and this cake was also broken into 2 pieces by the ash removing system at shut down.

In order to gain more information about the parameters influencing ash melting and slagging, selected slag samples from the pilot-scale test runs and molten ash from the lab-scale test runs were analysed by means of scanning electron microscopy (SEM) and energy dispersive X-ray spectrometry (EDX). The results of these analyses show that the dominating element in the molten parts of the ash and in the slag is Si followed by K and Ca. The sample from Cardoon (CAP) differs compared to the other samples, as the molten ash from Cardoon also contains major concentrations of Na and Al, which are of minor relevance in the other ashes. Other minor elements are Mg, P and Fe..

Mass and element balances over the pilot-scale combustion plant

Mass and element balances over the pilot-scale combustion plant have been performed. The results clearly indicate that the major part of the main ash forming elements (Ca, Si, K, Na, Mg, P, Al and Fe) and of the less volatile trace elements (Mn, Cu, Ni and Cr) are found in the bottom ash, while the more volatile trace metals (Zn, Pb, Cd and Ba) show a clear tendency towards higher concentrations in the fly ashes. This fractionation of the volatile trace elements is less profound in the test runs with SGP compared to the test runs with GR and MI. The reason for this is presumably the higher amount of slag produced during the test runs with SGP and thereby, a higher amount of encapsulation of these elements into slag occurred.

It has been shown, that about 70% of S and about 75% of Cl are emitted as gaseous SO₂ and HCl respectively. For S the solid part is mainly retained in the bottom ash while for Cl this fraction is either emitted as fly ash particles or involved in deposit formation in the heat exchanger.

The concentrations of the trace metals Zn, Mn, Ba, Cu, Ni, Cr, Pb and Cd in the fly ashes are significantly higher than in the bottom ash. In comparison to Austrian limiting values for ash utilisation on agricultural fields and in forests, the limiting values for Zn, Pb and Cd are exceeded by all fly ash samples but not by the bottom ash samples from the test runs. However, fly ashes only comprise 1-8 % of the total amount of ash produced and the main part of the ash could thus be utilised.

5.2.3 Pyrolysis tests

The bench scale rig was used to determine the optimum pyrolysis temperature for each project feedstock, i.e. the reaction temperature giving the maximum yield of organic liquids in the product bio-oil and hence the highest energy conversion efficiency.

For all tests, mass balances were produced and the product liquids were subjected to water and char content tests and basic chemical analysis (C,H,O,N,S) to permit calculation of energy content. By-product chars and gasses were also analysed for

composition and energy content. From these data full energy balances were performed.

In addition, the ash content and composition of the various feedstocks were correlated with the pyrolysis liquid yields, and a clear relationship between the organic liquid yield and the alkali metal content of the feedstock emerged. High alkali metals equated to low organic liquid yield, a relationship that agrees with the literature data which predicts the decomposition of liquid products into gas and water in secondary gas phase reactions (catalysed by alkali metals). Organic liquid yields of less than 40wt% were obtained for feedstock with an alkali metal content of >0.7wt%

Problems were experienced in the pyrolysis of cynara (Cardoon) even though the feedstock had been selected to try to minimize ash and alkali metals. Bed agglomeration and de-fluidisation were observed on several experiments. Electron-microscopic and X-ray diffraction analysis of the lightly sintered bed material did not reveal the exact cause, but the agglomeration may be due to stickiness from the particular distribution of organic vapours & aerosols or to local melting of ash components in char particles.

Samples of switchgrass and miscanthus with low ash and alkali metal content were pyrolysed on the 1kg/h rig, which closely resembles (proposed) commercial bubbling bed pyrolysis plants and has a representative product liquid collection system. Relatively high product yields of up to c. 65wt% (53wt% organics) were observed for these feedstocks. These figures are in agreement with those for a range of other low ash/alkali feedstocks reported in the literature.

In both cases these feedstocks had been taken from biomass stands that had experienced a degree of natural rain leaching prior to harvest, which contributed to their low alkali metal content.

A number of washing tests were performed on arundo (giant reed) and switchgrass samples with high ash (up to 5%) and alkali metals (up to 1.18%) content.

Washing tests, performed on particle sizes from 0.5mm to 2 mm showed that the use of simple stirred wash / rinse cycles could reduce ash by up to 35% and alkali metals by up to c.80% in washing times of less than one hour and with water usage less than that reported in the literature for straw.

5.2.4 Gasification tests

The operation of the gasifier with giant reed, miscanthus and switchgrass was very normal and experiments were also stopped in a regular way. Differences that could be observed between the crops were the following:

- The experiments with giant reed gave much higher heating value of the gas. The CH₄, C₂/C₃ concentrations were significantly higher (1% methane ~0.5 MJ/Nm³). The effect of C₂/C₃ was even higher. To some extent it might be caused by the lower operating temperature of the gasifier, but that contradicts

with the results of switchgrass and miscanthus; normally the higher the temperature the lower the methane concentration is. It is known from literature that certain minerals can catalyse the gasification of biomass; whether this is the case here is not clear.

- The tar content of giant reed is very high. Temperature plays an important role, but also minerals may be effective. High methane concentration is already an indication that high tar yields can be expected. Both observations (high tar, high methane) are therefore in line.
- Surprisingly, in neither case any chlorine could be detected. A significant difference is observed with respect to the measured concentrations of NH₃ and H₂S. For switchgrass and cardoon NH₃ content was in the order of 600-800, whereas for miscanthus and giant reed only 45-100 ppm could be detected. One explanation might be that after the run with cardoon the complete bed material was replaced. There might be some difference in bed material or the bed material might have some absorbing capacity. The other explanation might be the nature of the ash. Some ashes may absorb for example quite some chlorine and sulphur.
- The tests with cardoon stopped automatically after about an hour due to a very high-pressure drop over the gasifier. Inspection revealed that large sintered particles were built up inside the gasifier and the cyclone.

5.3 Financial/Economic analysis

Cost of Agricultural production

The following **Table 5.4** presents cost details of the *single crop production* analysis whereas **Tables 5.5 and 5.6** present cost details of the *multi-cropping systems* scenarios.

Table 5.4: Cost analysis of single crop agricultural production (euro/dry tonne)

	FRANCE	GREECE	ITALY	SPAIN
<i>Arundo donax L.</i>				
Annual Equivalent Yield	12,7	12,7	12,7	8,3
PRODUCTION				
Land	9,25	39,40	17,99	15,79
Labour	7,73	6,48	8,85	6,81
Equipment	3,25	6,94	4,01	5,60
Raw materials ⁽¹⁾	25,24	25,30	26,90	39,61
Total	45,47	78,12	57,75	67,81
<i>Cynara cardunculus L.</i>				
Annual Equivalent Yield	15,0	15,0	9,4	15,0
PRODUCTION				
Land	7,83	10,87	24,28	8,70
Labour	5,29	2,57	9,71	2,91
Equipment	2,55	2,53	5,01	2,69
Raw materials ⁽¹⁾	12,84	12,90	21,80	13,64
Total	28,51	28,87	60,80	27,94
<i>Miscanthus x giganteus</i>				
Annual Equivalent Yield	12,5	10,2	10,2	5,0
PRODUCTION				
Land	9,41	49,26	22,49	26,30
Labour	10,89	12,32	15,33	15,68
Equipment	2,63	12,10	4,12	7,65
Raw materials ⁽¹⁾	19,39	23,56	25,51	48,73
Total	42,32	97,24	67,45	98,36
<i>Panicum virgatum L.</i>				
Annual Equivalent Yield	10,9	11,0	10,9	4,4
PRODUCTION				
Land	10,75	45,29	20,90	29,64
Labour	7,81	6,85	8,95	11,11
Equipment	4,45	8,23	5,30	12,22
Raw materials ⁽¹⁾	9,01	8,99	10,90	22,56
Total	32,02	69,36	46,05	75,53

⁽¹⁾ Fertilizers, Herbicides, Rhizomes, Seeds, Water etc. Including Overheads

Table 5.5: Cost analysis of the multi-cropping system (Giant reed, Cardoon,

Miscanthus and Switchgrass) production (euro/dry tonne)

	FRANCE	GREECE	ITALY	SPAIN
Annual Equivalent Yield	12,8	12,2	10,8	8,2
PRODUCTION				
Land	9,31	36,21	21,42	20,11
Labour	7,93	7,06	10,71	9,13
Equipment	3,22	7,45	4,61	7,04
Raw materials ⁽¹⁾	16,62	17,69	21,28	31,14
Total	37,08	68,40	58,01	67,41

⁽¹⁾ Fertilizers, Herbicides, Rhizomes, Seeds, Water etc. Including Overheads

Table 5.6: Cost analysis of the multi-cropping system (Giant reed, Miscanthus and Switchgrass) production (euro/dry tonne)

	FRANCE	GREECE	ITALY	SPAIN
Annual Equivalent Yield	12,0	11,3	11,3	5,9
PRODUCTION				
Land	9,80	44,65	20,46	23,91
Labour	8,81	8,55	11,04	11,20
Equipment	3,44	9,09	4,48	8,49
Raw materials(1)	17,88	19,28	21,10	36,97
Total	39,94	81,57	57,08	80,57

⁽¹⁾ Fertilizers, Herbicides, Rhizomes, Seeds, Water etc. Including Overheads

Cost analysis of Harvesting, Storage and Transport

In order to determine economies of scale in harvesting and transport cost, three scale scenarios were analysed, as mentioned before. The **Table 5.7** presents the cost details of the *single crop systems* of Harvesting, Storage and Transport analysis.

Tables 5.8 and 5.9 present the cost details of the *multi-cropping systems* of Harvesting, Storage and Transport analysis, assuming equal quantities of each crop in each case.

Table 5.7: Cost analysis of single crop harvesting and transport (euro/dry tonne)

	FRANCE	GREECE	ITALY	SPAIN
<i>Arundo donax L. (Chips)</i>				
Large Scale				
Harvesting & Storage	16,20	11,65	14,47	13,30
Transport	21,25	24,60	22,51	23,65
Total	37,45	36,25	36,98	36,95
Medium Scale				
Harvesting & Storage	16,20	11,65	14,47	13,30
Transport	22,29	25,83	23,62	24,84
Total	38,50	37,48	38,09	38,14
Small Scale				
Harvesting & Storage	16,20	11,65	14,47	13,30
Pelleting	19,32	19,32	19,32	19,32
Transport	13,07	15,41	13,92	14,99
Total	48,60	46,37	47,71	47,61
<i>Cynara cardunculus L. (Bales)</i>				
Large Scale				
Harvesting & Storage	13,99	10,13	17,84	9,44
Transport	4,51	5,20	4,77	4,98
Total	18,50	15,33	22,61	14,42
Medium Scale				
Harvesting & Storage	13,99	10,13	17,84	9,44
Transport	3,69	4,27	3,91	4,11
Total	17,67	14,41	21,74	13,55
Small Scale				
Harvesting & Storage	20,13	14,33	24,20	12,97
Pelleting	19,32	19,32	19,32	19,32
Transport	13,07	15,41	13,92	14,99
Total	52,52	49,06	57,44	47,28
<i>Miscanthus x giganteus (Bales)</i>				
Large Scale				
Harvesting & Storage	13,39	11,23	13,93	18,21
Transport	4,51	5,20	4,77	4,98
Total	17,90	16,43	18,70	23,19
Medium Scale				
Harvesting & Storage	13,39	11,23	13,93	18,21
Transport	3,69	4,27	3,91	4,11
Total	17,08	15,50	17,84	22,32
Small Scale				
Harvesting & Storage	14,70	18,24	22,90	29,24
Pelleting	19,32	19,32	19,32	19,32
Transport	20,90	15,41	13,92	14,99
Total	54,92	52,97	56,14	63,55
<i>Panicum virgatum L. (Bales)</i>				
Large Scale				
Harvesting & Storage	11,30	8,19	10,18	14,51
Transport	4,51	5,20	4,77	4,98
Total	15,81	13,39	14,95	19,49
Medium Scale				
Harvesting & Storage	11,30	8,19	10,18	14,51
Transport	3,69	4,27	3,91	4,11
Total	14,99	12,46	14,09	18,63
Small Scale				
Harvesting & Storage	32,82	17,31	29,01	43,72
Pelleting	19,32	19,32	19,32	19,32
Transport	13,07	15,41	13,92	14,99
Total	65,22	52,03	62,25	78,03

Table 5.8: Cost analysis of multi-cropping systems (Giant reed, Cardoon, Miscanthus

and Switchgrass) harvesting and transport (euro/dry tonne)

	FRANCE	GREECE	ITALY	SPAIN
Large Scale				
Harvesting & Storage	13,72	10,30	14,11	13,87
Transport	7,95	9,21	8,42	8,86
Total	21,67	19,51	22,52	22,73
Medium Scale				
Harvesting & Storage	13,72	10,30	14,11	13,87
Transport	17,46	20,48	18,57	19,85
Total	31,18	30,78	32,67	33,72
Small Scale				
Harvesting & Storage	20,96	15,38	22,65	24,81
Pelleting	19,32	19,32	19,32	19,32
Transport	15,03	15,41	13,92	14,99
Total	55,32	50,11	55,89	59,12

Table 5.9: Cost analysis of multi-cropping systems (Giant reed, Miscanthus and Switchgrass) harvesting and transport (euro/dry tonne)

	FRANCE	GREECE	ITALY	SPAIN
Large Scale				
Harvesting & Storage	13,63	10,36	12,86	15,34
Transport	11,12	12,88	11,78	12,38
Total	24,75	23,23	24,64	27,72
Medium Scale				
Harvesting & Storage	13,63	10,36	12,86	15,34
Transport	14,31	16,74	15,20	16,20
Total	27,94	27,09	28,06	31,54

5.4. Environmental Assessment

5.4.1 Life Cycle Assessment

- **Biofuels versus fossil fuels**

In virtually all cases, all perennial crops under concern reveal advantages with respect to saving non-renewable energy carriers and greenhouse gases and disadvantages regarding acidification, eutrophication, and ozone depletion. In the categories photo smog and human and ecotoxicity the results are non-uniform.

An objective decision for or against a particular fuel cannot be made. However, based on a subjective value system a decision is possible. If, for example, energy saving and greenhouse effect is given the highest priority, all of the biofuels studied perform better than the alternative fossil fuels.

- ***Biofuels and technologies compared among each other***

The results of the environmental implications depend only on relatively few factors. Parameters as e.g. the infrastructure, transports, the amount of irrigation, and the variety of crops play only a secondary role.

Especially significant are: yield, efficiency and co-product usage in conversion, and the fossil energy substituted by the bioenergy.

From the environmental analysis, a number of general statements can be derived, however, in many cases there are opposing results. For instance, with certain exceptions the following results are valid:

- Which crop is cultivated for bioenergy utilisation has only small influences on the results. Yield is decisive.
- The efficiency of gasification and pyrolysis has a strong influence on the results of the life cycle comparisons.
- For combined heat/power (CHP) production, extremely large bandwidths may show. This fact depends on the relation in which power and heat are used and – on the fossil side – replaced. In any case, if not all of the products can be used (e.g. in the case of heat losses) less fossil energy will be saved.
- If producing heat direct combustion mostly saves more energy and greenhouse gases than gasification and pyrolysis, but has higher other environmental impacts.
- For direct combustion and gasification, energy savings in power production are lower than 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, a little worse if substituting natural gas.

- ***Country-specific aspects***

The results of the environmental implications concerning LCA are influenced by a few country-specific parameters:

- Since the single countries have different shares of coal, oil, natural gas, and nuclear power in their electric power mix, replacing these different power mixes by electricity from biomass leads to possibly very different results.
- As is generally known, yield depends among other things such as fertilisation and irrigation especially on climate and soil conditions, which vary strongly between regions. For this reason, the results show large regional differences, independent if single crops or multi-crop systems are regarded.

Compared to the total environmental impacts in the different countries, the results vary significantly between the countries. They may vary within time as the environmental impacts are changing through the years.

5.4.2 Environmental impact assessment

- *Crop-specific assessment*

Table 5.10. Crop specific environmental impact, ranked into five categories (++ , + , 0 , - , --).

	<i>Miscanthus</i>	Giant reed	Switchgrass	Cardoon	Typical annual row crop	Typical natural state
Soil erosion	+	+	++	++	—	++
Soil chemistry	++	++	++	++	—	++
Soil compaction	0	0	+	+	—	++
Nutrient leaching / eutrophication	+	+	+	+	—	++
Water demand	—	0	++	++	—	++
Weed control / pesticides	0	0	-	-	—	++
Species diversity / habitat quality	-	-	-	0	—	++

++ is assigned to the typical natural state and thus refers to the optimal situation for a given location. In contrast, -- characterises the impacts of typical annual row crops as the reference for the most unfavourable scenario.

The differences between the environmental implications of the four perennial bioenergy crops are relatively small (**Table 5.10**). The main disadvantage of *Miscanthus* is the high demand for water. Cardoon has some advantages with respect to biodiversity, since the crop is indigenous to the Mediterranean flora and provides food for hymenopterous insects and granivorous birds. However, the demand for weed control may be higher compared to the other energy crops, except for Panicum.

- *Comparison of environmental impacts of different thermochemical conversion technologies*

Regarding climatic factors, all conversion technologies have beneficial effects compared to fossil driven units, due to the reduction of greenhouse gas emissions.

The comparison of the conversion technologies by the technology-related factors is summarised in **Table 5.11**. The actual relevance of the technology-related factors and their environmental impact depend mainly on the specific environmental situation at the planned site of the conversion unit.

Table 5.11. Conversion and transport related environmental impact of the different conversion technologies, ranked into 3 comparative categories (+, o, -).

Technology related factor	combustion	gasification	pyrolysis	Possible environmental effect
Emission of noise and odours	(+)	(+)	(-)	Annoyance by an increase of environmental noise or gaseous emissions
Amount of traffic (noise and gaseous emissions)	-	-	+	Annoyance by an increase of environmental noise or gaseous emissions
Size and height of conversion plants	o	o	o	Soil compaction or sealing Loss of vegetation Loss of habitat Landscape disturbance
Risks of explosions or fires in the plant or in storage areas	o	o	o	Injury

“+” is assigned to the best option concerning the factor; “-“ is assigned to unfavourable options concerning the factor; “o” indicates no differences between technologies. Values in brackets indicate considerably small differences between technologies and a strong site-dependency.

- ***Landscape and cultivation aspects***

Despite relatively minor crop specific differences, there might be clear advantages for one or the other energy crop on a specific site. For example, in dry areas with sandy, erosion-endangered soils, switchgrass and cardoon would be the best options, whereas *Miscanthus* and *Arundo* could be excluded. On the other hand, in areas with a surplus of water, *Miscanthus* and *Arundo* could be used best. Thus, the growth of energy crops would be ideally combined with other environmental services such as the potential of giant reed to recycle wastewaters or the adaptation of one energy crop for a particular species of interest.

Care has to be taken about the potential of the crops to introduce into adjacent natural habitats and replace natural plant communities. This is true for *Arundo* and possibly for switchgrass. For relatively dry areas, large scale plantations of all crops may be problematic due to the fire hazard. The risk of fire is lower in Cardoon, because of its annual growth cycle.

- ***Country-specific aspects***

Regarding the environmental impact assessment, the bioenergy crops do not show significant discrepancies among the suitability for a specific Mediterranean country.

6. Conclusions

6.1 Biomass production

Although the field trials accounted for only two-three full growing periods, all four perennial crops showed good adaptability and biomass yields were sufficient to indicate the potential biomass production when the selected perennial crops are grown in South European climatic conditions.

When comparing the crops, cardoon seemed to be the less suitable crop for thermochemical conversion, mainly because of its high ash content. Additionally, the plant can hardly overcome killing winter frosts and even if it does, re-growth and biomass production in the year of frosts will be lost or negligible.

Moreover the productivity of giant reed and switchgrass did not depend on the nitrogen fertilization, thus high dry matter yields were obtained with low costs and energy consumptions, in areas where water is not a limiting factor. However in areas with dry summers irrigation plays a key role to achieve high yields.

Comparing irrigation and nitrogen effect, in a field trial carried out by CRES, the influence of irrigation was more pronounced compared to nitrogen fertilisation. Plants can use nitrogen fertilisation only in combination with irrigation. The irrigated and highly nitrogen fertilised treatments exhibited high values in most growth and yield characteristics indicating that both irrigation and nitrogen fertilisation are important for achieving high yields. Switchgrass was influenced in a lesser extent in comparison to giant reed.

Cardoon showed a too short cycle for this latitude, thus future breeding programs will be desirable to select longer cycle varieties for energy conversion.

Regarding establishment, giant reed and miscanthus are planted by rhizomes while switchgrass and cardoon are established by seeds. Therefore establishment of the first two crops is more expensive and labour-dependent, while sowing can be done completely mechanized using conventional sowing machines for grasses.

Harvesting of all crops can be done by traditional harvesting machines used for forage crops, though certain modifications have to be considered in order to avoid high incorporation of soil particles in the harvested material.

In order to assess the effects of environmental factors on switchgrass productivity, a Geographical Information System is being developed by the University of Bologna. Preliminary results showed a significant high spatial variability of the yield. Next steps will be focused on explaining this variability by overlapping the several thematic maps of the GIS.

In another trial on genotype screening also carried out by University of Bologna, genotypes selected in USA for energy destination had the highest production of dry matter and they did not show to be damaged by winter frost. The double cut per year did not increase significantly the total yield compared to single cut. However the results concerned only one year, while information on the yearly vigor and plant duration as affected by cut is also desirable.

6.2 Biomass conversion

6.2.1 Fuel characterisation

The main quality aspects of biomass fuels are the heating value and the ash content. On an ash free and dry basis the heating values of the crops investigated are similar to wheat straw but lower than wood.

The ash content of perennial crops is comparable with the ash content of wheat straw and significantly higher than the one of wood chips. However, there is a very strong influence of the harvesting method used and the conditions during the harvest. If not considered, significant amounts of soil can contaminate the crop during the harvest and thereby significantly increase the ash content. Due to this fact the way samples are collected (mechanically or by hand) should always be considered when evaluating fuel analyses results.

Based on the analyses performed, the concentration levels of relevant elements (especially K, Na and Cl) in the perennial crops imply that generally high particulate emission levels, corrosion and deposit formation rates are to be expected during combustion of these fuels.

The influence on the chemical composition of the fuel from the crop itself is especially seen for the concentrations of Na and Ca. Cardoon seems to contain much higher concentrations of these elements compared to the other crops investigated.

The concentration of heavy metals in the fuel is most probably due to the conditions of the soil on which the crop is grown on. It is well known that the pH and the concentrations of heavy metals in the soil have a strong effect on the uptake of heavy metals in plants and that different types of crops can show different accumulations of heavy metals on the same soil. Moreover, the uptake of Cl could also be influenced by the soil conditions which also include the type of fertilisers used. If KCl is used as fertiliser the concentration of Cl in the crop will increase as well. For all the four crops investigated, a tendency towards higher concentrations of Cl was found in samples from Spain. This could be due to a higher concentration of Cl in the soil of the Spanish test fields compared to the test fields in the other countries.

Recommendations

The chemical composition and also the morphology of the perennial crops investigated are comparable to the commonly used biomass fuel wheat straw and significantly different to wood. According to this, combustion technologies developed for straw combustion should be applicable for the combustion of perennial crops as well.

First of all, the harvest methods for the perennial crops have to be further developed and tested in order to avoid contamination of the fuel. Secondly, for large-scale applications the fuel should be stored and transported as bales and presumably also combusted as bales. For small-scale applications pelletising of the fuel prior to transportation is the best solution as the chopped material has much too low mass and energy densities for efficient transport, storage and fuel feeding.

When combusting these fuels, care has to be taken concerning emissions (especially NO_x and particulates). Also operational problems such as slagging and fouling are to be expected. Especially in small-scale applications these problems are difficult to solve and thereby techniques for improving the quality of the fuel such as leaching,

usage of additives or blending with other fuels should be investigated in the future work.

6.2.2 Combustion tests

Compared to wood fuels the combustion of perennial crops is much more challenging. The main reason is the high ash content of these crops. Also the chemical composition of the ash as well as the fuel itself has significant influence on their combustion characteristics. Severe problems with ash melting are to be expected when burning these fuels. These problems could be avoided by an appropriate design of the furnace. The results from the evaluation of the test runs performed indicates, that a temperature below about 1,100°C is necessary in order to prevent ash melting on the grate. It is therefore recommended that technologies used for wheat straw combustion such as water cooled furnace walls and a water cooled grate should be used for the combustion of these crops. Another possibility to avoid slagging problems would be to blend these fuels with a less problematic fuel such as wood pellets.

However, the test runs at the pilot-scale combustion unit have shown, that Switchgrass, Miscanthus and Giant Reed could be utilised in such a combustion unit but not the specific Cardoon sample tested, which was characterised by extremely high K, Si and Cl-contents.

High KCl concentrations were found in the boiler tube deposits. KCl can be very corrosive on metal surfaces and a tendency to increased corrosion was also indicated by increased amounts of Fe in the heat exchanger ash collected during the pilot-scale test runs. Such increased corrosion should thus be considered during the design of a plant, by e.g. using thicker boiler tubes.

Results from deposit probe sampling revealed a correlation between the concentration of emitted fly ash and the deposit build up on deposit probes. Due to this, blending with wood (which reduces the fly ash concentrations) or other techniques which could reduce the amount of K and Cl in the fuel (e.g. leaching or usage of additives) are recommended to be considered in order to decrease this possible problem.

The major emission problem discovered from the pilot-scale test runs were NO_x-emissions and, in the case of Cardoon, dust emissions, which exceeded the limiting values for small-scale combustion plants in Austria. However, appropriate secondary NO_x and dust emissions control technologies are already available.

From the results of the test runs it can be concluded, that the combustion characteristics as well as the problems occurring during combustion are similar for all four perennial crops investigated. The design of a combustion plant using all these crops would be similar as well except for the Cardoon tested, which is not suitable for combustion.

The main problem would be to design a suitable fuel feeding system. Bales are probably the easiest and most efficient way for transporting for large-scale combustion plants. In the case of small-scale plants pelletised fuels are the best suitable solution in order to ensure high enough bulk and energy densities of the fuels, which makes them suitable for the fuel feeding systems usually applied. Although pelletised perennial crops have a higher energy density than chopped fuels, still problems with reaching the full load of the plants designed for wood pellets are

observed. Consequently, new designs with a larger combustion chamber in relation to the boiler capacity would be necessary for an optimised combustion of these crops. Moreover, also the increased amount of ash produced from these crops has to be considered in the design of the ash removal systems of the plant.

According to the test run at the pilot-scale combustion plant about 87 to 95% of the ashes produced remained as bottom ash. Due to the generally low concentrations of environmentally relevant heavy metals in these ashes, the ashes could be recycled and used as fertilisers on the soils where the crops were grown.

6.2.3 Pyrolysis tests

These feedstocks are generally suitable for fast pyrolysis provided that their alkali metal content can be controlled to less than c. 0.5wt%.

This might be achieved by:

- Appropriate agricultural practices, e.g. minimising use of potassium containing fertiliser and late and careful harvesting to maximise senescence and minimise soil contamination of the crop
- Over-wintering the crop to achieve rain leaching of alkali metals
- A washing process prior to pyrolysis

In the case of cynara alkali metals levels seen in literature data (and in this project) are very high and this caused low yields and may have been responsible for agglomeration problems. For this feedstock it is unlikely that any of the ash/alkali metals reduction techniques mentioned above could be applied because:

- Cynara harvesting is more difficult because of the structure/aspect of the plant and soil contamination appears likely.
- For low aspect plants (such as cynara), winter rain is more likely to cause lodging and contamination from soil-splash. In addition cynara is likely to be grown in low-rainfall areas to exploit its drought-tolerance.
- Mechanised washing of cynara is likely to be more expensive than for the other crops because the stems contain a high fraction of low-density absorbent pith making them difficult to dry.

For these reasons Cynara was not considered suitable for fast pyrolysis.

6.2.4 Gasification tests

Ash melting behaviour of a large number of samples have been determined. Large variations can be observed for different samples of the same energy crop. As such this may cause an additional complication for the use of energy crops in thermal conversion processes. In general, the ash of cardoon does not melt, but sinter at a low temperature. This will certainly complicate its use.

All energy crops have been gasified in a fluidized bed gasifier. Arundo, Miscanthus and switch grass could be gasified without operational problems. The experiment with cardoon was stopped automatically after about one hour due to bed agglomeration.

Recommendations

Based on the gasification results from several projects in combination with the ash content and behaviour of this kind of crops, it is believed that a modified gasification concept is required.

The basis of the new concept is to separate minerals and -most of the- organics at a rather low temperature and avoid that minerals will reach a high temperature anywhere in the process.

The process consists of the following steps:

1. Biomass is fed to a flash pyrolysis reactor, where organic vapors are formed. Besides vapors also charcoal –containing the ash- is produced. Preferably, a flash pyrolysis reactor is applied which does not use a carrier gas otherwise the vapors are too much diluted.
2. Charcoal is fed to a low temperature combustor generating the heat for the pyrolysis reactor. Basically, the charcoal is supplying the heat for evaporating the biomass and water. It is expected that at least 20-30 wt% water can be allowed in the feedstock. Water in the feedstock may have a positive effect on the gasification step.
3. The last step is the gasification of organic vapors into a clean fuel gas. Vapors are easier to gasify than solids because homogeneous conditions) improved control) can be easily achieved. The use of a catalyst can be considered.

Indicative calculations have shown that the overall cold-gas efficiency of such system can be at least similar to the gasification system used in this project. BTG has recently started the development of such a gasification system.

6.3 Financial/Economic analysis

Based on the cost analysis of the agricultural production, in France Giant reed has the lowest cost of production (45 €/dry tonne) because it is cultivated without irrigation. In Greece the crop has the highest cost of production (78 €/dry tonne) because it is fully irrigated and it is charged with high land rent. In Italy the crop is only irrigated during the establishment period and the production cost is relatively low (58 €/dry tonne) while in Spain the crop has higher cost (68 €/dry tonne) because it is cultivated without irrigation and has low yields. In general, Giant reed also has high establishment cost because of the rhizomes cost.

Cardoon is the most cost effective of the four crops in France, Greece and Spain (about 28 €/dry tonne) because although it is cultivated under non irrigated conditions it has highest productivity. Italy is the only exception where the crop has low yields without irrigation and the cost resulted to be higher (61 €/dry tonne).

Miscanthus production and cost analysis results are very similar to Giant reed. The cost of establishment is also increased because of the rhizomes cost. In France the cost of the production is the lowest (42 €/dry tonne) because of the absence of irrigation. Spain has the highest cost of production (98 €/dry tonne) because of the low productivity, while in Greece the cost (97 €/dry tonne) is increased because of the use of expensive irrigated land. The cost in Italy is 67 €/dry tonne.

In general, Switchgrass cost of production is lower than Giant reed and Miscanthus mainly because it is established with seeds. The crop resulted to have the lowest cost of production (32 €/dry tonne) in France where it is produced without irrigation. Italy also has low cost of production (46 €/dry tonne), where the crop is irrigated only during the establishment year. The cost of production is high in Greece (69 €/dry tonne) because it is cultivated on irrigated land and in Spain (76 €/dry tonne) where the productivity of the crop is very low because it is produced under dry conditions.

Based on the Harvesting and Transport cost analysis, Giant reed has the highest cost for the Large and Medium scale analysis because the harvested material is chips while the other three crops are harvested in bales. It is also resulted that there are no significant differences between Large (50,000 dry tonnes/year) and Medium (15,000 dry tonnes/year) scale costs (absence of economies of scale between those two cases). The case of the Small scale (4,000 dry tonnes/year – Pellets production) is more costly because of the additional pelleting cost (19.32 €/dry tonne) and the increased cost of harvesting and transport (economies of scale are present in this case).

The multi-cropping analysis was performed for two cases. The first case covers the production of all crops where France has the lowest cost (37 €/dry tonne) of biomass production while Spain resulted to be the most expensive country for biomass production (67 €/dry tonne). In this case, Greece has the lowest cost of harvesting and transport cost. The second case covers the combined production of all crops except Cardoon. The cost of biomass production is higher than the first case because the absence of cost effective Cardoon in this analysis.

According to the comparison of the production of energy and selected conventional crops, the break-even price of energy crops was estimated for every case. Based on this analysis, in France the most interesting scenario is the replacement of durum wheat with Switchgrass (46 €/dry tonne break-even price). In Greece, the replacement of durum wheat with Cardoon (46 €/dry tonne break-even price) may be an alternative solution for the farmer, while in Italy, Switchgrass may replace durum wheat with 46 €/dry tonne break-even price. It is also very interesting that in Spain Switchgrass has negative break-even price (-13 €/dry tonne) when durum wheat is replaced. The comparison between energy crops and maize or cotton resulted to be less interesting for every case.

6. 4 Environmental assessment

6.4.1 LCA

Biofuels can help saving energy and greenhouse gases. To some extent they are, however, associated to environmental disadvantages. An objective decision for or against a particular fuel cannot be made. However, based on a subjective value system a decision is possible. If, for example, energy savings and greenhouse effect are given the highest priority, all of the biofuels studied perform better than the alternative fossil fuels.

Depending on the crop, the conversion technology, and usage, the environmental effects show at times large or even very large differences. The largest environmental advantages with the smallest environmental disadvantages at the same time can be achieved as follows:

- For obtaining a high environmental benefit, one should grow crops permitting high yields while being ecologically sound.
- In order to produce heat, one should combust biomass directly instead of using the products of gasification or pyrolysis. Only for very advanced technology conversion efficiency can get significantly higher and there is still waste heat left over for heating uses. If one desires to produce electric power or combined heat/power from biomass, the decision whether direct combustion, gasification, or pyrolysis is the best option depends on the individual case.
- For utilising the bioenergy crop the optimal way, every effort should be taken to optimise the efficiency of gasification and pyrolysis and to utilise the waste heat of the conversion processes and pyrolysis residues.
- Given a certain conversion technology, the optimal usage (heat, power, or combined heat/power) depends to a large extent on the individual case.
- If biomass is to be gasified it should be used for heat production at the site of the plant; if it is pyrolysed it should be used rather for power production. If the biomass is to be combusted directly it depends on the single case if heat production or combined heat/power production are preferable.
- For the sake of the greenhouse effect especially light oil should be replaced, only in the second run natural gas.
- If one attaches highest environmental value to the saving of depletable energy resources one should, in the best case, produce electric power from biomass in France in order to replace the French power mix. If, instead, one deems the greenhouse gases most important one should replace the Greek power mix.

The general outcome, e.g. the advantages for biofuels regarding energy savings and greenhouse gases, can generally speaking also be transferred to other bioenergy chains. An exact quantification of the respective life-cycle assessment and a site-specific environmental impact assessment, however, have to be undertaken for each individual case.

6.4.2 EIA

Energy crops can be used to manage or direct regional landscape ecology if the system is properly designed. Potential services include buffers around similarly structured natural habitats, linkages between fragments of natural habitat, or the creation of new habitats. How effectively the energy crop serves such roles does not only depend on the particular crop, but also on how it is managed (including use of chemicals, equipment, and harvesting cycle). Some general recommendations include (Wolfe 1993):

- Energy crops should be concentrated on current, idled, or former agricultural, pasture, or other “simplified” or “marginal” lands. Energy crops should not be grown on naturally structured primary-growth forest land, wetlands, or other natural lands.
- Energy crops should combine multiple vegetative structures to enhance landscape diversity as needed by particular species. This could include various

combinations of short-rotation woody crops, perennial grasses, and other dedicated energy crops, as well as inclusions of natural habitat.

- If possible, energy crop fields should be arranged as buffers around similarly structured natural habitats and linkages between fragments of natural habitat.
- Ideally, energy crops should provide artificial environmental functions important for a given location (erosion control, enhanced or reduced transpiration, wastewater recycling systems).
- Energy crops could also be used to provide structure to conventional agricultural monoculture through the addition of shelterbelts and fencerow plantings.
- Similarly, monoculture of energy crops should have shelterbelts or fencerows of other types of vegetation.
- Landscape structure can also be made more diverse by harvesting adjacent stands on different rotation cycles, including leaving some stands for longer periods if possible.
- Energy crops should be studied carefully at all appropriate scales and on a long-term basis to better understand the best means of improving appropriate habitats for desired species, both for the energy crop itself and for related agricultural, managed forest, and natural lands. This should also be done on a regional basis, as appropriate.

7. List of deliverables

No	Deliverable title	Planned Delivery Date	Actual Delivery Date
D1	Updated timetable	1	1
D2	Detailed literature review	1-3	18
D3	Protocols for all the tasks	1	3
D4	Report on the crops establishment, cultivation, harvesting and pre-treatment requirements	18, 30, 42	12, 24, 36
D5	Data on the costs of establishment, cultivation, harvesting and pre-treatment requirements	18, 30, 42	12, 24, 36
D6	Data on the local environmental implications from the production of crops	18, 30, 42	12, 24, 36
D7	Report on the characterization of the feedstock	18, 30, 42	12, 18, 30, 42
D8	Report on the results from combustion tests at lab-scale furnace	30	30
D9	Report on the results from combustion tests at pilot-scale furnace and working out of guidelines for manufacturers	39	39
D10	Report on the results from pyrolysis tests at lab-scale	30	30
D11	Report on the results from gasification tests at pilot-scale	30	30
D12	Report on the technical evaluation of the overall integrated bio-energy chain performance from biomass in the field to a derived heat and/or power product	42	42
D13	Economic analysis for the whole chain of each perennial crop (production, harvesting, storage and utilization)	15, 27, 39	15, 27, 39
D14	Economic comparison between the selected perennial crops and other conventional crops with similar cultural practices	18, 30, 42	18, 30, 42
D15	Scenarios for alternative land use in agriculture regions of S.EU	42	42
D16	Overall performance model to provide consistent comparison between different bio-energy chains	42	42
D17	Environmental analyses for each perennial energy crop in dependency of country specific conditions, thermo-chemical conversion technologies, farming methods, by-products used etc.	42	42
D18	List of the best options of a combination of biofuels and technology for each country and region.	42	42
D19	Consolidation of results derived from all work-packages	45	45
D20	Handbook	45	45
D21	Annual reports and minutes from all project meetings	Reports Minutes	12, 24, 36 1, 15, 18, 24, 30, 36, 43
D22	Final report	45	45
D23	Publication in scientific journals, contribution to National, EU and international conferences, setting www page etc	24-45	6-45

8. Dissemination and Use of the Results

The following dissemination activities have been carried out:

During the **first** year of the project:

- Presentation of the project objectives in the 12th European Biomass Conference in Amsterdam with a poster presentation:
‘Christou, M. Mardikis, M and E. Alexopoulou (2002). Bio-energy chains from perennial crops in South Europe. Proc. of the 12th. EC on *Biomass for Energy, Industry and Climate Protection*. Volume I, 338-341’
- Publication of a project summary in the 13th issue of Pyne.
- UPM has carried out some activities concerning the state-of-the-art of cardoon crop. The contents of these activities did not involve the experimental work of the project but they contribute to a further knowledge of the crop and so, they are expected to be of help for the success of WP1.
 - Fernandez J., Curt M.D., Luque S., Sánchez G., López C. and Hidalgo M. (2002): **Multilocal study of the contents in N, P. & K of *Cynara cardunculus L.* biomass.** Proc. of the 12th. EC on *Biomass for Energy, Industry and Climate Protection*. Volume I, 198-201
 - Curt M.D., Fernandez J. and Sánchez G. (2002): **The potential of *Cynara cardunculus L.* for seed oil production in a perennial cultivation system.** *Biomass and Bioenergy* 23(1), 33-46

During the **second** year of the project:

- Presentations in the 8th Conference on environmental science and technology, 8-10 September 2003, Lemnos island, Greece.
 - Christou M., Mardikis M., Alexopoulou E., Cosentino, S. L, Copani, V and E. Sanzone (2003). **Environmental studies on *Arundo donax*.** Proc. of the 8th *Conference on environmental science and technology*. Volume B, p.102-110
 - Soldatos, P. and V. Lychnaras (2003). **Technical-economic analysis for renewable energy chains: The case of bio energy.** Proc. of the 8th *Conference on environmental science and technology*. Volume B, p.759-765
- Presentation of the project in the Bio-energy enlarged perspectives - Contractors meeting and brokerage event in Budapest, Hungary, 16-17 October 2003.
- Presentations in the 2nd World Conference and Technology Exhibition on Biomass for Energy, Industry and Climate Protection 10-14 May 2004, Rome. Italy:
 - Christou M., Fernandez J, Gosse G., Venturi G., Bridgwater A.V, Scheurlen K., Obernberger I., Van de Beld B., Soldatos P.G, Reinhardt G. (2004) **Bio-energy chains from perennial crops in South Europe.** Proc. of the 2nd EC on *Biomass for Energy, Industry and Climate Protection*. Volume I, 604.

- Venturi P., Monti A. and G. Venturi (2004) **Evaluation of harvesting and post-harvesting chains for energy destination of switchgrass**. Proc. of the 2nd EC on *Biomass for Energy, Industry and Climate Protection*. Volume I, 234
 - Minelli M., Rapparini L. and G. Venturi. **Weed management in switchgrass crop**. Proc. of the 2nd EC on *Biomass for Energy, Industry and Climate Protection*. Volume I, 439
 - Grigatti M., Barbanti L., Pritoni G. and G. Venturi (2004) **Comparison of Switchgrass (*Panicum virgatum*) genotypes as potential energy biomass**. Proc. of the 2nd EC on *Biomass for Energy, Industry and Climate Protection*. Volume I, 261
 - Coulson M., Dahl J. and B. Van de Beld (2004) **Ash characteristics of perennial energy crops and their influence on thermal processing**. Proc. of the 2nd EC on *Biomass for Energy, Industry and Climate Protection*. Volume I, 359
 - Dahl J. and I. Obernberger (2004) **Evaluation of the combustion characteristics of four perennial energy crops (*Arundo donax*, *Cynara cardunculus*, *Miscanthus x giganteus* and *Panicum virgatum*)**. Proc. of the 2nd EC on *Biomass for Energy, Industry and Climate Protection*. Volume I, 1265
 - Coulson M. and A.V. Bridgwater (2004) **Fast Pyrolysis of annually harvested crops for bioenergy applications**. Proc. of the 2nd EC on *Biomass for Energy, Industry and Climate Protection*. Volume I, 1098
 - Soldatos, P., Lychnaras, V., Asimakis, D and M. Christou (2004) **Bee - Biomass Economic Evaluation: A Model for the Economic Analysis of Biomass Cultivation**. Proc. of the 2nd EC on *Biomass for Energy, Industry and Climate Protection*. Volume I, 604
- Presentation of the project in the two EU-events organized by the European Commission in Russia and China, namely:
 - ‘Bio-energy workshop EU-Russia’
 - ‘EU China Workshop on liquid biofuels’.
 - Presentation of the project in seminars and general events on bioenergy, as:
 - World Sustainable energy days in Wels, 03-05.03.2004
 - The national workshop on pellets held in CRES premises the 27th January 2005, in the frame of the ‘Pellets for Europe’ EU project.
 - 3rd National Conference on Renewable Energy Sources -RENES held in Athens, 23-25.02.2005

- Presentations in the 14th European Conference and Technology Exhibition on Biomass for Energy, Industry and Climate Protection 17-21 October 2005, Paris. France:
 - Christou M., Fernandez J, Gosse G., Venturi G., Bridgwater A.V, Scheurlen K., Obernberger I., Van de Beld B., Soldatos P.G, Reinhardt G. (2005). **Bio-energy chains from perennial crops in South Europe.**
 - Christou M., Mardikis M. and E. Alexopoulou (2005) **Biomass production from perennial crops in Greece.**

9. Management and co-ordination aspects

A review of the management and co-ordination aspects since the start of the project is to be included in up to 4 pages:

9.1. The performance of the consortium and the individual partners in terms of dedication to the project, motivation, supply of deliverables, as well as relevant organization of management and main communication aspects should be reviewed.

- Organization of seven technical meetings:
 - Kick-off meeting in Athens, Greece, 21-22 February 2002 (month 3)
 - 2nd project meeting in Bologna, Italy, 24-26 October 2002 (month 11)
 - 3rd project meeting in Enschede, The Netherlands, 8-9 May 2003 (month 18)
 - MTA meeting Nea Makri, Greece, 16-18 July 2003 (month 20)
 - 5th project meeting in Madrid, Spain, 26-28 November 2003 (month 24)
 - 6th project meeting in Graz, Austria, 21-24 March 2004 (month 28)
 - 7th project meeting in Stratford-Upon-Avon, UK, 7-9 March 2005 (month 40).
 - 8th meeting in Freizing, Germany, 11-12 April 2005 for only the Task leaders.
 - Final meeting in Mykonos, Greece, 6-9 October 2005 (month 47)
- Updating the work plan that defines the work to be completed, the protocol of the tasks, the responsibilities of the partners and the milestones.
- Financial management of the project
- Consolidation of the literature reviews on the tested crops, technologies and financial/environmental assessments.

As stated in the Technical Annex, one day after each meeting -except for the kick-off meeting- the members of the Steering Committee meets to monitor the recent technical and scientific matters, review the progress of the work before the relative documents are delivered to the EU and set up the work to be done until the following meeting.

In all meetings, visits at partners' field/facilities were also organized.

All decisions related to the project results, in terms of presentation, publication or exploitation inside or outside the initial plan, are made on the basis of the participation of all members of the consortium.

Besides the technical meetings, a day-to-day communication among all partners of the consortium has been established, covering all the technical and managerial aspects of the project, so as to ensure that work is carried out according to schedule.

Close contact between the biomass producers and conversion technologies groups have also been established in order to investigate and specify the possibilities for the growers to produce a fuel with proper size and moisture quality suitable for the combustion, pyrolysis and gasification tests and the pilot scale test runs.