EUROPEAN ENERGY CROPS: A SYNTHESIS

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Abstract—The European Energy Crops Overview (EECO) project was carried out with 20 partners from fourteen EU countries during 1996. The EECO-project provides the state-of-the-art on energy crops activities in Europe. More than 30 potential energy crop species have been investigated in Europe, but only a few have achieved commercial status so far. The introduction of energy crops in agriculture is relatively easy in the case of well-known agricultural crops such as rape and grain crops, but new crops are hampered by both technical and non-technical barriers. Production, pre-treatment and use of woody and herbaceous energy crops for power and heat generation is still mainly in the pilot to demonstration phase, while use of sugar and oil rich crops for transport purposes has been developed at a commercial scale already. Production, pre-treatment and use of SRC is fully developed in Sweden and in the pilot to demonstration phase in the north-west European countries. Herbaceous crops are tested up to a large scale in the Scandinavian countries, Germany, Austria and the Netherlands. Biodiesel is produced on a commercial scale in France, Germany, Austria and Italy, while bioethanol is produced at a commercial scale in France. In southern Europe, emphasis is on the production aspects of energy crops; only a limited number of efforts on use of energy crops have been realized so far. © 1997 Published by Elsevier Science Ltd.

Keywords—Energy crops; production; pre-treatment; processing; use; power; heat; transport fuels; Europe.

1. INTRODUCTION

This document summarizes the findings of 14 country reports of the European Energy Crops Overview (EECO) Project. The project was funded by the European Commission FAIR programme and many national institutions and was carried out from January to October 1996. Twenty partners from fourteen EU countries took part in this concerted action. The objectives of this project were to give an overview of the state-of-the-art on energy crops in Europe and to identify new fields for further research and development.

The goals of the project were: to summarize the achievements on energy crops production, processing and use reported in the fourteen country reports; to draw conclusions on the current status of activities with respect to energy crops in Europe and to develop recommendations on how to proceed in this field.

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This review is intended as a state-of-the-art overview for policy makers and planners who need complete information on energy crops in Europe. In addition, it is intended as a starting resource for potential farmers and end-users of energy crops, consultants to the agricultural and energy sector and manufacturers and suppliers of equipment which is used in these sectors. In this synthesis document, the most interesting and promising developments in energy crops in Europe are presented. As the document focuses on the main developments, the reader is referred to the individual country reports in the bibliography for detailed information.

The crops discussed are distinguished as follows: woody crops (SRC: willow and poplar, eucalyptus); herbaceous crops (like Miscanthus, Phalaris/RGC, Cyperus, Triticale); oilseed crops (rape seed, sunflowers) for the production of biodiesel; and sugar-containing crops (like sugar beet, sweet sorghum) for the production of bioethanol via the fermentation route. The following aspects are covered: agri-
cultural; technical; environmental; energy; and economical. For each crop, the most interesting and promising scientific and practical achievements on all aspects are presented. The achievements are followed by analyses.

This review focuses on mostly technical and techno-economic data. For more emphasis on non-technical barriers, readers are referred to the results of the Agricultural and Forestry Biomass (AFB) Network (contact C.A. Foster).

2. PRODUCTION

This section summarizes the information given on primary production of energy crops in all EU countries. Many crops have been investigated and within each crop, the information has been obtained under a wide range of pedoclimatic conditions. Therefore, overall conclusions on yield level cannot be given and the specific information from each country is presented individually. Often, the information originates from research plots from which detailed information is available. However, the same results will usually not be obtained in practical farming as the level of crop care is different. Whenever possible, we have described the level at which the information was obtained, e.g. research plots/commercial conditions/irrigated/rain fed. Figure 1 shows an example of how yield level can differ between different framework conditions within the same crop.

A wide range of energy crops has been tested in Europe (Table 1). Only the crops that have been tested more intensively are described in this synthesis report. In some cases, traditional agricultural crops have been adapted for energy use. This is the case for oilseed crops such as rape and sunflower and for grain crops like Triticale and wheat which can be combusted. Mostly, the production of these crops for energy does not differ much from the production for food or fodder. Therefore, this section describes in more detail the state of the art of new crops for energy rather than of traditional agricultural crops, the production of which is quite well known. Whenever specific information on effects from production inputs on fuel quality of traditional agricultural crops has been given, this knowledge is, of course, presented.

2.1. Woody crops

2.1.1. Willow (Salix spp.)

2.1.2. Achievements. Willow is grown mainly in the northern parts of the EU. In Sweden, the development of willow production has been given high priority since 1975 through intensive research programmes. Since 1991, the production has been commercialized and currently about 17 000 ha have been established. The plant breeding company Svalof-Weibull runs a breeding programme on willow and has introduced new clones on the market with improved yield and resistance to pests and frost. A number of new companies are involved in the production of cuttings and

![Diagram: Total growth in trial plots: 11 t DM]

The figure relates to Phalaris under Swedish conditions (from G. Haddad, Vår är det för röftten? Final report from a research programme on energygrass).

Fig. 1. Yield levels as function of framework conditions.
Table 1. Energy crop species in Europe. Areas are based on information from the national reports

<table>
<thead>
<tr>
<th>Latin name</th>
<th>Common English name</th>
<th>Hectares</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brassica spp.</td>
<td>Oilseed rape seed</td>
<td>800 000</td>
</tr>
<tr>
<td>Eucalyptus spp.</td>
<td>Eucalyptus*</td>
<td>500 000</td>
</tr>
<tr>
<td>Helianthus annuus</td>
<td>Sunflower</td>
<td>91 000</td>
</tr>
<tr>
<td>Salix spp.</td>
<td>Willow</td>
<td>18 000</td>
</tr>
<tr>
<td>Triticum aestivum</td>
<td>Winter wheat (GWC)</td>
<td>350</td>
</tr>
<tr>
<td>Secale cereale</td>
<td>Winter rye (GWC)</td>
<td>6250</td>
</tr>
<tr>
<td>Triticosecale</td>
<td>Triticale (GWC)</td>
<td>350</td>
</tr>
<tr>
<td>Hordeum vulgare</td>
<td>Spring barley (GWC)</td>
<td>170</td>
</tr>
<tr>
<td>Beta vulgaris</td>
<td>Sugar beet</td>
<td>65</td>
</tr>
<tr>
<td>Phalaris arundinacea</td>
<td>Reed Canary Grass</td>
<td>22</td>
</tr>
<tr>
<td>Populus spp.</td>
<td>Poplar</td>
<td>2</td>
</tr>
<tr>
<td>Cannabis sativa</td>
<td>Hemp*</td>
<td>550</td>
</tr>
<tr>
<td>Miscanthus spp.</td>
<td>Miscanthus</td>
<td>15</td>
</tr>
<tr>
<td>Hibiscus cannabinus</td>
<td>Kenaf*</td>
<td>9400</td>
</tr>
<tr>
<td>Cynara cardunculus</td>
<td>Cardoon</td>
<td>65</td>
</tr>
<tr>
<td>Sorghum bicolor</td>
<td>Sweet sorghum</td>
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</tr>
<tr>
<td>Atriplex halimus</td>
<td>Alder</td>
<td>350</td>
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<tr>
<td>Arundo donax</td>
<td>Giant reed</td>
<td>2</td>
</tr>
<tr>
<td>Helianthus tuberosus</td>
<td>Jerusalem artichoke</td>
<td>2</td>
</tr>
<tr>
<td>Camelina sativa</td>
<td>False flax</td>
<td>350</td>
</tr>
<tr>
<td>Robinia pseudoacacia</td>
<td>Black locust</td>
<td>2</td>
</tr>
<tr>
<td>Bambusa spp.</td>
<td>Bambusa</td>
<td>9400</td>
</tr>
<tr>
<td>Reynoutria japonica</td>
<td>Switchgrass</td>
<td>800 000</td>
</tr>
<tr>
<td>Salix viminalis</td>
<td>Willow</td>
<td>500 000</td>
</tr>
<tr>
<td>Agrostemma githago</td>
<td>Corn cockle</td>
<td>18000</td>
</tr>
<tr>
<td>Spartium junceum</td>
<td>Brook</td>
<td>91 000</td>
</tr>
<tr>
<td>Solanum tuberosum</td>
<td>Potato</td>
<td>4050</td>
</tr>
<tr>
<td>Spartina spp.</td>
<td>Spartina</td>
<td>3</td>
</tr>
<tr>
<td>Panicum virgatum</td>
<td>Switchgrass</td>
<td>65</td>
</tr>
<tr>
<td>Acacia spp.; Betula spp.; Onopordum acanthium</td>
<td>Birch</td>
<td>9400</td>
</tr>
<tr>
<td>Nicotiana glauca</td>
<td>Wild tobacco</td>
<td>800 000</td>
</tr>
<tr>
<td>Opuntia ficus-indica</td>
<td>Prickly pear</td>
<td>6250</td>
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<tr>
<td>Sinapis alba</td>
<td>White mustard</td>
<td>18000</td>
</tr>
<tr>
<td>Linum usitatissimum</td>
<td>Flax</td>
<td>91 000</td>
</tr>
<tr>
<td>Zea mays</td>
<td>Maize</td>
<td>4050</td>
</tr>
<tr>
<td>Phragmites australis</td>
<td>Reed</td>
<td>350</td>
</tr>
</tbody>
</table>

*Eucalyptus is mainly grown in Portugal for pulp production. Hemp and Kenaf are mainly grown for fiber purposes.

Water availability is the limiting factor for the production; and heterogeneity of fields has a strong influence on yield. Fertilization below recommended levels has decreased yield by about 20%. The fertilizer effect is strongly dependent on successful weed treatment. Highest yields have been obtained on organic soils.

The production economy has been subsidized in Sweden by an establishment grant, and willow production is economic at the current market prices for forest wood chips. As grants may not be expected in the future, cost reduction is essential. This has been achieved by higher efficiency in the production and planting of cuttings. Furthermore, a new concept is now offered commercially in Sweden whereby chopped willow material is laid horizontally in the ground using a sugar cane planting machine. This establishment is offered at 540 ECU/ha including cuttings, but the method has not been tested in any official trials (1 ECU = $1.15).

Salix viminalis is mainly used in Sweden, but tests are also performed on S. dasyclados. Some of the new promising clones are crossings between S. schwerinii and S. viminalis.

In the U.K., SRC (short rotation crops), mainly willow, are considered the most promising energy crop at the current development stage. About 200 ha have been established, but the establishment of a further 2000 ha are expected during the next 3 years. Annual yields between 8 and 20 odt/ha/yr have been obtained and, on average, 10 odt/ha/yr is expected under commercial conditions. Several willow species and clones have been tested from which recommendations are given on the most disease resistant genotypes and on which willow species to select for specific soil types. Several herbicides have been tested and recommendations for practice are available. Limited or no effects of fertilization have so far been obtained, but these results are from fertile soils during the first rotation. Willow is considered environmentally friendly as no insecticides or fungicides are used and only a few herbicide treatments are necessary during the whole crop cycle. Studies have revealed that good habitats are created for insects, birds and mammals. Furthermore, the crop is considered for the safe disposal of ashes and sewage sludge, which can serve as a nutrient source to the crop. Rabbits and deer can damage the young fields and fencing off is
considered, but the cost can be prohibitive. Willow rust is considered to be the most serious disease affecting willow production and clonal mixing is advised.

In Finland extensive R&D has been performed on clone selection from more than 800 genotypes, breeding, soil types and fertilization. It was hoped that willow could recultivate exhausted peatlands, but these seem to be too acidic. Furthermore, severe frost damage occurred on the most productive clones. Accordingly, only about 20 ha has been established in total. It is reported that a willow field can be reclaimed by treating the stubs with Roundup® and later removal of the dead stubs.

In Denmark, about 400 ha has been planted and mean yield is currently 7–8 odt/ha/yr. Some stands are used for sludge application, which is ploughed under in tracks through the crop. In addition, wastewater treatment is being tried in demonstration projects. Low nitrate leaching has been measured both in stands with sludge applied and in stands with fertilizer applied. The Swedish low-cost establishment is being compared with conventional establishment by cuttings and with planting whole stems horizontally. Further cost reduction can be obtained by using higher row distances than advised from Sweden. This seems to improve crop water availability without significant yield reduction. Ploughing up subsoil before planting has proved effective in reducing weed problems.

In Ireland, peatland recultivation has also been tried with willow, but annual yields of only about 5 odt/ha can be obtained which is about half of the expected yield on agricultural land. The Irish climate is considered optimal for willow production. Experiments have taken place since the 1970s. However, there is no commercial production and less than 100 ha has been established.

In the Netherlands, about 1800 ha of willow is exploited commercially, but not for energy purposes. Recently initiated research looks at planting distances, weed treatments and fertilization. Apart from S. viminalis, S. alba is also being investigated. In Italy, small research areas of S. alba are investigated indicating annual yields of 15–20 odt/ha.

2.1.3. Analysis. The Swedish example of an extensive R&D programme and commercial introduction of willow is instructive for other countries. It has shown that introduction of a new crop (in contrast to the adaptation of traditional agricultural crops) is a long process and takes up a lot of resources. On the other hand, the whole of the EU is now benefiting from the Swedish experiences and willow is one of the most highly developed new crops.

Although the crop has become highly technically developed, farmers' perception of the crop is still a major barrier to increasing the cropped area. The long crop rotation, the lack of long-term legislation and the risk of increased pest problems are among the barriers. A good establishment and effective weed control during the first years are essential and these aspects must be focused on in further R&D. Low-cost establishment will ease the production economy and reduce the investment risk. Establishment costs have been reduced by 50% during the period from 1990 to 1995 in Sweden and new establishment methods seem to reduce the costs even further. Several pests attack willow and this may be expected to become an increasing problem if larger areas are established. The development of strategies, such as clonal mixing, to avoid severe pest spreading and attack, is necessary.

Willow production seems to be environmentally friendly in terms of emissions to water, carbon balance and in creating habitats for fauna and, to some extent, flora. However, these aspects should be further focused on in research to establish guidelines for best management practices and to be able to quantify the effects. This may provide a basis for improved production economy as grants for environmentally safe production can be expected. In addition, the use of the crop as a vegetation filter to wastewater or for the disposal of sludge and ashes should be investigated further.

The economic analysis shows large variations between countries, the estimated costs per odt delivered 50 km to the plant ranging from 38 to 86 ECU. The lowest price is estimated in Belgium where, however, no commercial production takes place and the Swedish price of 59 ECU/odt is probably more realistic. When the subsidy for establishment in Sweden is included, production costs are reduced to about 50 ECU/odt. The highest costs are estimated in the U.K. despite a grant for the establishment included in the calculation. This is mainly due to expected costs for storage, which in several other countries have
not been included as direct delivery to the plant during winter is anticipated.

The low establishment costs in Sweden should be noted as these are mainly due to large-scale rationalization and the same reduction can be expected in other countries if scaling up takes place. The anticipated price of cuttings is 0.036 ECU per cutting in Sweden and 0.15 ECU in Austria. On the other hand, the evaluation of the first commercial experiences in Sweden has shown that the introduction of new technical development to farmers is a major bottleneck. Accordingly, emphasis on good farmers’ advisory services when new crops are introduced is a key point.

2.2. Poplar (Populus spp.)

2.2.1. Achievements. Poplar can be grown in warmer climates than willow. In some countries like the U.K., Ireland, Belgium, Austria and Germany, both species are grown. In Germany, poplar has been tested on different soil types, of which former agricultural land was better suited than formerly forested land. Poplar did not tolerate high contents of heavy metals in soils. Plant density varied between 700 and 1700 plants/ha. Harvest intervals of 4–6 yrs are common. Annual yields in the first rotation have been between 3 and 30 odt/ha with an expected mean of 10–15 odt/ha. Weed treatment is necessary in the year of establishment, while the selected clones in Germany are rarely attacked by pests. Wild animals may, however, cause problems. Establishment costs are estimated to about 1600 ECU/ha.

In the Netherlands, selection and breeding of poplar has been going on for 50 yrs and there is a number of productive and disease resistant clones available. These include hybrids between P. deltoides, P. nigra and P. trichocarpa. About 32,000 ha has been established, but not for energy purposes. However, several research projects aiming at energy use have been initiated lately. In the U.K., hybrids of the same species as in The Netherlands are grown and estimated annual yields under commercial conditions are in the range of 6–12 odt/ha. A planting density of 2000 plants/ha is used. In Austria, 840 ha of poplar and willow is grown on which annual yields of between 2 and 12 odt/ha have been registered.

2.2.2. Analysis. Poplar has been investigated in central European countries and in the U.K. for many years, but the information on poplar still appears rather scattered and not as focused on energy use as for willow. There appears to be possibilities for valuable transfer of information and breeding material between countries, compared with willow, poplar seems to be more resistant to pests and diseases.

2.2.3. Eucalypts (Eucalyptus spp.)

2.2.4. Achievements. The largest European areas of eucalypts in short rotation have been established in Portugal where approximately 500,000 ha is grown for pulp production. The species E. globulus is used, which is very frost sensitive and cannot be grown north of the Iberian peninsula. The usual planting density is 1100 plants/ha and harvest is normally performed with 8–10 yrs of interval. Yields vary very much with climatic and soil conditions. Potential annual production with irrigation and fertilization is over 20 odt/ha.

In France, research on eucalypts started in 1972. The first plantations were established in 1983, but all these froze out during very cold winters between 1985 and 1987. Most of the breeding research is now focused on frost resistance and biomass production. Two clones have been selected. A total of 507 ha is now planted in France for pulp production; the density is 1250 plants/ha and estimated annual yields under commercial conditions are 8–14 odt/ha.

In Greece, small test plots of E. globulus and E. camadulensis have been established in 1990 and on good soils annual yields above 20 odt/ha/yr have been registered in a 2 yr rotation. On a less fertile field, the yield in second rotation was, however, only 6 odt/yr. The effects of irrigation and nitrogen fertilization are being investigated and so far no significant influence on productivity has been observed. In Italy, 3 ha of research fields of the same species as in Greece have been established in 1993–1994. Annual yields of 15–20 odt/ha have been registered so far.

2.2.5. Analysis. The very large commercial areas of eucalypt in Portugal have provided substantial experiences on production, harvest and delivery to the pulp plants. These experi-
ences can easily be transferred to the use of eucalypts for energy purposes. However, initial use of the wood fibres for paper or the like and later energy use of the by-products is a sensible combination and should not be changed. In France, production costs for eucalypts are estimated to be 46 ECU/odt. If good productivity without irrigation in Greece continues, the crop appears to be an interesting option compared with crops with a higher demand for irrigation.

2.3. Herbaceous crops

2.3.1. Miscanthus (Miscanthus spp.)

2.3.2. Achievements. Miscanthus was introduced to Europe as an ornamental plant some 50 yrs ago. It is a C4 perennial grass and therefore adapted to warmer climates. Southern parts of Sweden, Denmark, southern U.K. and Ireland appear to be the most northern regions for this crop.

The first experiments on growing Miscanthus for pulp or energy were carried out in Denmark in the late 1960s. The first experimental field was established in 1983. In most years, yields have been between 7 and 14 odt/ha at the spring harvest. However, since 1992 yields have been lower due to drought and late spring frosts, but apparently also due to an age effect, especially at the highest planting density. Mean yields under commercial conditions in Denmark are 7-8 odt/ha on sandy soils and 8-9 odt/ha on clay soils. These yields constitute only about half of the biological production as the leaves and top are lost during winter. Harvest in autumn is being experimented with to increase yield, but the material is wet and has a higher mineral content. However, production costs are calculated to be reduced from 76 to 44 ECU/odt when changing from spring to winter harvest owing to the yield increase and to reduced storage costs as direct delivery to the heating plant is anticipated.

For the first experiments the species Miscanthus x ogiformis ‘Giganteus’ was used, but a range of clones of M. sinensis have been tested in Denmark showing improved winter survival, much lower content of Cl and K and apparently yield at the same level as Giganteus. These clones and new material from Japan are now included in a breeding programme. The establishment of Miscanthus has been performed by plantlets, but the costs were prohibitive for the crop to become a competitive energy crop. A low-cost method for the establishment (about 1000 ECU/ha) is being tested indicating a faster crop establishment and better winter survival than from plantlets. A mother field is rotary cultivated, the rhizome pieces sampled by a stone picker and planted at about 10 cm depth in the new field. The planting operation still needs to be optimized.

Weed treatment during establishment is essential and Miscanthus seems to tolerate all herbicides for use in grass crops. In Denmark, Roundup® may be used in spring as long as the sprouts are not green. Caution should be taken in warmer climates as green material on the old shoots may take up Roundup®. Mechanical weed treatment with a long tine harrow and row cultivation is possible. The removal of the crop can be performed by repeated rotary cultivations followed by a Fusilade treatment if a dicot crop is sown. Nitrate leaching from fully established Miscanthus is very low.

Currently about 30 ha are established in Denmark, while in Germany there are about 100 ha. A comprehensive research programme on Miscanthus was conducted in Germany between 1989 and 1994 by the Veba Ol Company. It has provided valuable information also on some significant barriers to increased crop use: crop establishment is expensive (2500-5000 ECU/ha) which, when depreciated over crop lifetime, constitutes 50-60% of annual variable costs. Furthermore, significant overwintering problems have occurred during the first winter.

Experimental plots at different German locations have been studied for their yield potential, providing information of relations between climatic conditions and yield. The soil types influenced the crop as establishment was faster on sandy soils (irrigation during establishment is, however, recommended), while higher yields were obtained on clay soils later on. Winter losses of leaves and tops are about 30%. Yields in the range between 6 and 17 odt/ha at spring harvest are recorded. Harvest is recommended in March where crop water content is low and the mineral content reduced compared with autumn. Long-term experience on nutrient demands is still lacking, but the demands will depend on the amounts removed by harvest, as only few other losses occur. In Germany, one fertilizer application is recommended within 4 weeks of sprouting.
The crop is considered as environmentally sound, except for the first year where the ground cover is sparse and weed treatment is necessary. The crop has so far not suffered from any severe pests.

In the Netherlands, about 27 ha have been established. Plant death during the first winter has occurred when planting plantlets or rhizomes, the survival rate varying with soil type, fertilization and climate, but not in a consistent manner. Miscanthus has grown well on all soil types except for heavy clay. Yields of 16–17 odt/ha have been recorded in research plots and 10–12 odt/ha are expected under commercial conditions. Harvest is normally undertaken when the straw is dry in April, but this gives a harvest window of 1 month or less. Whole stem harvesting is under development to increase the harvest period to four months. The bales can then be dried in the field.

Recently, detailed investigations on low-cost establishment from rhizomes have taken place in The Netherlands. These confirm the Danish results of about 80% cost reduction and improved establishment. In the Dutch approach, a lily bulb harvester or adapted potato harvester is used to collect the rhizomes. Planting is performed by an adapted Cramer potato planter with a capacity of 0.3 ha/h. Multiplication rates of up to 50 can be achieved. Costs per rhizome of 0.04 ECU (as compared with current plantlet prices of about 0.30 ECU) are calculated, assuming a multiplication rate of 35. When rhizome pieces of 40–100 g were planted within few days after harvesting, the emergence rate was 70–95%.

In Austria, high yields have been recorded, around 20 odt/ha after the third year. However, this may only be obtained on the best soils which are also suitable for wheat production. Harvest is considered in February/March when the water content is still around 40%. Plots of 1–2 ha in total have been established since 1989. In France, about 10 ha have been established and yields of 10–22 odt/ha have been measured.

In Belgium, Greece, Ireland, the U.K., Italy, Portugal and Spain, small research plots of Giganteus have been established as part of the European Miscanthus network. In Ireland, yield under research conditions has been 4 odt/ha in the first year, 10 odt/ha in the second year and 15 odt/ha in the third year. In Belgium, yields of 16–20 odt/ha have been measured. In Greece, 1–2 ha are cultivated.

Yields of between 18 and 29 odt/ha have been registered with irrigation when harvested in November and winter loss of the crop may reach 50%. Nitrogen fertilization only affected yield marginally. In Italy, annual yields of 20–25 odt/ha are expected in commercial conditions and up to 30 odt has been registered in research plots. The main focus of research is currently on reducing the costs of establishment. In Portugal, the crop sprouts in March and mean yield has been 24 t/ha with a moisture content of about 44% by harvest in December.

In the U.K., approximately 1 ha has been established in research plots and yields of 11–13 odt/ha have been registered. It has been shown that the light-saturated photosynthesis in Miscanthus, unlike in maize, was not affected by temperatures as low as 14°C. Pests and diseases were found to have no significant impact on the crop. However, some shoots were affected by larvae, as has also been observed in Denmark, but no plants were killed.

2.3.3. Analysis. Two main barriers have so far been prohibitive to further developments of Miscanthus production: one is the widespread problem of low first winter survival that has occurred mainly in the northern parts of EU. The other is the costs of establishment that have been much higher than for other perennial crops like Salix or RCG.

Genotype screening indicates that winter survival can be improved. The genetic base of Miscanthus must be increased by selection and breeding. Apart from better adaptation to different climatic conditions, this will reduce risks of future pest problems. Furthermore, fuel quality can be improved as lower contents of Cl and K are observed in new genotypes.

The costs of Miscanthus establishment given in the national reports varies between 32 and 977 ECU/ha when depreciated over the crop lifetime. This enormous variation can occur because new low-cost methods are anticipated in the calculations from the Netherlands and Denmark, which brings down the annual costs to a lower level than in willow and in annual crops. The methods so far seem very promising, as, apart from the lower costs, a better winter survival rate is obtained when compared with earlier results on rhizome planting. This is probably due to the use of larger rhizomes and shorter time between rhizome harvest and planting. There is, however, a need
for scaling up the methods and to test them under different conditions throughout Europe.

Another way of reducing costs for establishment could be by sowing the crop. This is not possible for Miscanthus ‘Giganteus’, which is sterile, but may be so for other species and possibly by new lines from breeding programmes. Like other perennial crops, Miscanthus can be produced with low inputs and low losses of minerals and pesticides to the environment. The crop is therefore suitable for production in environmentally vulnerable areas, e.g. for ground water protection. However, the establishment phase is environmentally critical. Even though risks of leaching, soil erosion and humus degradation during establishment can be “depreciated” over the full crop lifetime, they should be minimized. Therefore, efforts to improve establishment should include attempts to reduce environmental impact. Examples could be intercropping to reduce leaching and soil erosion and the use of non-chemical weed treatments.

Miscanthus is most often harvested in spring when it is dry. The harvest window is limited though and part of the crop is lost during winter. Harvest during winter could both increase the harvest window and the yield, which will increase the economic feasibility of production. Development of early harvest should be coordinated with analyses of combustion quality as this is closely related to harvest time.

The economic analysis shows large variation between countries, the estimated costs per odt (delivered 50 km to the plant) ranging from 34 to 73 ECU. The variations are mainly due to differences in establishment costs and in the anticipated yields. If low-cost establishment is implemented in the countries with high yield potentials, low crop production costs will be possible.

2.3.4. Reed canary grass (RCG) (Phalaris arundinacea L.)

2.3.5. Achievements. In Sweden, studies of grasses for energy production started in 1981 and revealed that RCG was the most suitable. RCG is native in Sweden as in many other parts of northern Europe, but varieties for fodder use have been selected and are commercially available. Svalöf Weibull AB is currently breeding new varieties suitable for energy production which are planned for market introduction in the year 2001. Several thousand hectares of RCG have been established in Sweden because of earlier grants for converting from food crops into non-food crops. However, only very little of the grass is used for energy, as the Swedish market for straw/grass combustion is not developed.

One advantage of RCG compared with other perennial crops like Salix or Miscanthus is the low costs for establishment as the crop is sown. During the first year the above ground production is limited, while from the second year and onwards, energy crop production of 8–12 odt/ha has been measured in field trials. Spring harvest has proven most feasible for energy purposes and yields of 6–8 odt/ha are expected when harvested under commercial conditions. When harvested in spring, the grass is dry and can be stored easily and minerals are leached from the grass during winter which reduces the fertilizer requirements and improves the combustion quality.

RCG can be grown on most soil types. However, it thrives particularly on wet, humus-rich soils, while soils with more than 40% clay seem to hamper establishment. Ash content was found to be influenced by soil types as the highest contents were found on clay soils. Total ash content did not change much during winter but the contents of Cl and K were reduced by about a factor of six. Weed treatment is advised for the year of establishment, whereafter the crop is very competitive and no weed treatment is necessary. No serious attacks of pests have so far been observed in RCG in Sweden.

Recommended fertilization under Swedish conditions and with spring harvest are 150, 100 and 30 kg/ha of N,P and K, respectively, in the first year and 80, 30 and 10 kg/ha during the rest of the production period. Grass ash has been used for fertilization. The final removal of the crop is also quite easily performed by conventional soil tillage operations.

In Finland, RCG was investigated for non-food purposes from the beginning of the 1990s together with 15 other plant species. Of these, RCG turned out to be the most promising for Finnish conditions. The best growth is obtained on organic soils (pH well over 4) where experimental yields of 8–14 odt/ha have been recorded at spring harvest. On mineral soils only 5–8 odt/ha have been recorded. It has been found that the crop tolerates drought
European energy crops: a synthesis

periods and flooding for some weeks. One advantage mentioned, compared with willow for example, is that it keeps the rural landscape open, as it only reaches its maximum height of about 2 m during a short period in autumn. Currently, about 50 ha has been established as demonstration and research projects.

Several cultivars, mainly bred for fodder purposes, have been tested but since 1994 there has been a breeding program to develop cultivars for non-food purposes. This program is based on native Finnish material selected from about 100 locations. In Finland, weed treatment is only necessary during the year of establishment. Apart from chemical treatment, cutting of the stand before August will reduce weeds. The Finnish recommendation for N fertilization is 70–100 kg/ha on mineral soils and 40–60 kg/ha on organic soils.

Since 1995, small research plots have been established in Sweden, Finland, the U.K., Ireland, Germany and Denmark through an EU project on RCG. Investigations following a common protocol include genotype and harvest time trials on which yields and mineral contents are measured.

2.3.6. Analysis. In the most northern parts of the EU, RCG seems to be a very attractive option for an energy crop. In more central parts of Europe, other species probably give higher yields, but RCG may be of interest anyway because of the low costs of establishment, high competitiveness to weeds, no requirement for special agricultural machinery and easy reclamation if the land must be returned to food crops. As the crop does not grow very high, it can be used in parts of the agricultural landscape where high woody crops or Miscanthus are undesirable. There is, however, a need to investigate harvesting feasibility in regions where moist climate and soils may cause problems in very early spring when RCG must be harvested. Breeding of RCG has been initiated in Sweden and Finland, but these efforts should be broadened by including material native to other northern European countries.

As RCG seems quite tolerant to flooding, further investigation for wastewater treatment will be of value. This should include determination of the balances of nutrients and water at different input levels. This will also be of value for the evaluation of RCG production in ground water protection areas.

The economic analysis indicated production costs in Sweden of 66 ECU/odt and in Finland of 59 ECU/odt. These costs are 7–8 ECU higher than for willow chips in both countries. This difference is due to lower expected yields and anticipated storage costs of RCG, in contrast to the anticipated direct delivery of willow to the combustion plant. The good storage ability of RCG improves security of delivery. Costs for establishment, weed treatment and crop removal are lower in RCG than in willow.

2.3.7. Cynara (Cynara cardunculus)

2.3.8. Achievements. Cynara is a perennial thistle-like plant adapted to dry Mediterranean conditions. In its natural cycle, it sprouts in autumn and passes the winter as a rosette. In the spring, a floral scape is developed which dries during summer and the whole crop can be harvested dry (10–15% water) in the late summer. Winter rains are used for the energy crop production and no irrigation during summer is necessary.

In Spain, about 50 ha of experimental fields have been established. Light, deep and limy soils are the best. The crop is sown either in spring or autumn, depending on the climatic conditions of the location. Between 7500 and 15 000 plants/ha are established, depending on water availability. Between 7500 and 15 000 plants/ha are established, depending on water availability. At least 400 mm of precipitation during autumn, winter and spring is required to obtain a good yield. It is reported that with 450 mm rainfall a production of about 20 odt/ha can be harvested. The harvested material consists of about 33% leaves, 22% stems and 45% capitula. The seeds in the capitula (2.5–3 t/ha) contain oil which may be extracted. A supplementary use of the crop is as forage, using the green leaves developed in autumn.

During the year of establishment, weed treatment is necessary. Several herbicides are available, but a mechanical approach is also possible. In the first harvests, large amounts of green forage were taken in winter. The amount of dry energy crop biomass harvested in summer was reduced (compared with
treatments without forage harvest), but the total dry matter yield was not decreased. Best yields were obtained at planting densities of 30,000 plants/ha or more, which, however, may change when the crop grows older. Yields of about 30 odt/ha were obtained; however, the rainfall during the growing season was not reported. In Greece, *Cynara* is considered promising for non-irrigated, low fertility, sloping soils, as perennial growth reduces the risk of soil erosion. The major barrier is considered to be the lack of appropriate harvesting equipment.

The same experimental investigations as in Greece are performed in Portugal and Italy, which also participate in the Cynara network. So far, only preliminary results are available. However, in Italy, the crop is considered to be of interest due to the low costs of establishment by seeding.

2.3.9. Analysis. *Cynara* seems to be well adapted to the dry Mediterranean conditions where most precipitation occurs during the winter season. It can therefore produce high yields without irrigation in contrast to crops like Miscanthus, sorghum and *Arundo donax*. The possibility of harvesting the crop for fodder increases its value at the farm level. As the harvest and use of the crop is not well developed, this should be given high priority in order to evaluate the whole bioenergy chain of the crop.

Another barrier seems to be the risk of pests recorded from Spain. Even though these may be successfully managed with pesticides, other solutions should be looked for to increase the environmental acceptability of the crop. At first, the effects of pests on production should be quantified to assess whether the pest treatment is really economic. Furthermore, evaluation of possible changes in the agricultural practices that will reduce pest impact should be undertaken. Breeding or selection of resistant genotypes may be another way of reducing the need for pesticides.

The economic calculations from Spain indicate costs of *Cynara* biomass (delivered 10 km to the energy plant) of about 24 ECU/odt. This is very competitive compared with other energy crops and due to the oil content of the crop, the energy value per odt is high. This further emphasizes the need for evaluation of harvest and use of this crop. The low costs are due to low establishment costs, low input of fertilizer and irrigation and a high yield.

2.3.10. *Sorghum (Sorghum bicolor)*

2.3.11. Achievements. Both sweet sorghum and fibre sorghum are being investigated for energy use. Sorghum is an annual C4 crop of tropical origin. It is therefore best adapted to southern Europe. However, in Mediterranean zones its main growing period coincides with the dry season and the crop will need to be irrigated. When irrigated very high yields can be obtained. In Spain, up to about 30 odt/ha of sweet sorghum (of which about 10 odt is sugar) has been harvested in experiments. Dry matter content was about 30%. The test fields were irrigated with 600 mm annually.

In Greece, sweet sorghum has been investigated during the last 8 yrs in experiments at different geographical locations. Eight different varieties have been tested of which six performed well. Establishment by seeds is easy and cheap. Lower plant densities than originally used (143,000 plants/ha) seems to improve yield. Weed control has been performed manually in the experiments. Irrigation is considered necessary and then yields up to about 30 odt/ha are obtained on fertile soils. Here, no effects of N fertilization are recorded. The crop is also reported to be adapted to poorer soils in Greece. An insect pest has occurred but has been treated biologically. Barriers to the production are susceptibility to lodging, the short processing period for ethanol and a lack of appropriate harvesting equipment.

In France, a total of about 15 ha of fibre sorghum is grown in experiments at about 20 locations. Yields of 6–15 odt/ha are obtained in northern France and 8–20 odt/ha in southern France. The crop can be grown with a total water supply of 400 mm which is less than for the production of maize. Planting densities of 150–200,000 plants/ha seems optimal, which is higher than in Greece. Normally between 50 and 100 kg N/ha is sufficient.

In Belgium, small research areas are grown with both fibre and sweet sorghum. Planting densities of 200,000 plants/ha are recommended. Fertilization is performed before sowing with 120, 100 and 200 kg/ha of N, P and K, respectively. Atrazine is used against weeds. Yields of 5–8 odt/ha are obtained from sweet sorghum in colder areas, while 12–15 odt/ha is obtained in the warmer regions.
Small trials of fibre sorghum have given yields of 12–15 odt/ha.

In Portugal, small plots of the sweet sorghum variety ‘Keller’ have been sown at a density of only 40,000 plants/ha, through the participation in the sweet sorghum network. With regular irrigation mean yields of 30 t/ha have been obtained.

In Italy, small plots of fibre and sweet sorghum are planted at various sites. The crop was grown and harvested with minimum adjustment of well-known agricultural techniques and annual yields up to 25 odt/ha were measured. An advantage of the crop is that it fits well into the crop rotation.

2.3.12. Analysis. Very high productivity of sorghum is possible in southern Europe under irrigated conditions. However, it needs to be evaluated as to whether the necessary water resources for bioenergy production of sorghum are available. One option, which has not yet been investigated, could be to irrigate the crop with wastewater.

As for energy grain (discussed below) and other annual crops, one of the major advantages of sorghum is that it fits well into conventional crop rotations. Being annual, it is also not so dependent on the long-term stability of the Common Agricultural Policy. Furthermore, existing agricultural machinery can be used for crop establishment, care and harvest.

The economic analysis indicates production costs per odt between 48 ECU in Spain and 65 ECU in France. Due to the different calculation methodologies used it is difficult to analyse the reason for the difference.

2.3.13. Energy grain (whole crop Triticale, wheat, rye or barley)

2.3.14. Achievements. The production of cereals for combustion or for fermentation may be performed in the same manner as for the production for food or fodder use. However, the quality criteria are not the same, especially when combustion is aimed at. For fermentation use, high grain yields must be obtained, while for combustion a high total yield is aimed at as both grain and straw are used.

In Germany, wheat, Triticale and rye are investigated. Wheat has the highest yield potential on good soils, while on poor soils, rye is the highest yielding crop. Triticale yields are intermediate; it attracts interest for energy purposes as it is not used for food production. Research on energy grain is targeted at the development of environmentally friendly management practices. The demand for inputs of pesticides is lower for rye and triticale than for wheat, as they are less susceptible to pests. A mean total yield of 12 odt/ha (5.5 odt/ha of grain) is expected under German conditions.

In Denmark, demonstration projects are running on about 500 ha of winter cereals. Total yields in 1995 varied between 5 and 18 (mean 10.9) odt/ha under commercial conditions. Grain loss during harvest was related to the harvest time and was more severe in wheat than in rye. The content of Cl and K was influenced by the cereal species, the variety, type of fertilizer, soil type and precipitation before harvest. A 50% reduction of Cl in the straw fraction was obtained by using chloride free fertilizer, but even more pronounced reductions were seen when the mature crop received 50–100 mm of precipitation.

In Austria, demonstration projects on wheat, rye and Triticale are conducted on about 20 ha and this area is expected to increase. Total yields of about 10 odt/ha are obtained in these projects. In France, 10 ha of triticale is grown in a demonstration project for heat production and total yields of 10–14 odt/ha are obtained.

2.3.15. Analysis. Cereals are highly developed crops owing to their use for food production and the knowledge of production is widespread among farmers. Therefore, energy grain production can easily be implemented in agriculture and high and stable yields can be expected. The production fits into standard crop rotations and it is flexible as planning for only one year at a time is necessary. However, even under the set-aside regulation, energy grain production is most often not profitable, given the current market prices of biomass for energy. Production costs per odt (land rent not included) are estimated at 76 ECU in Denmark and between 61 and 70 ECU in Germany depending on the yield. Further cost reduction is not very likely as the production is already optimized. Farmers may, however, wish to produce energy grain on set-aside land if they have machinery and labour available at marginal costs.

Some knowledge of the relationships between production factors and energy grain quality for combustion and fermentation is available, but a more comprehensive under-
standing is necessary for detailed advice on how to optimize combustion quality. Such information is important as the straw often contains high amounts of corrosive minerals which causes considerable problems during combustion or other thermal conversion processes. Environmentally friendly production systems can be adapted from food production and should be further developed since different quality criteria apply to energy grain.

2.3.16. Hemp (Cannabis sativa)

2.3.17. Achievements. Hemp has a long tradition as a fibre crop, but the energetic use of hemp is a new idea. For energetic use, harvesting of the whole crop is expected. The stem thickness and height of the hemp crop is similar to maize. The best time to harvest hemp for energetic use is not known yet. It depends on the hemp species, the harvesting method, the acceptable amount of field losses (e.g. of seeds) and the possibilities of additional drying.

In the Netherlands, research was carried out during 1987–1993, aimed at determining the potential of hemp for pulp production. Hemp for energy purposes has not been specifically investigated in the Netherlands, but results from pulp production research give an indication of what to expect in terms of costs and yields. Yields were found to be 10–17 odt/ha, with the highest yields on clay soils. Herbicides are normally not necessary as the crop can suppress weeds. However, fungi may cause problems in wet years, but this can apparently be tackled by breeding. For research on energy use, approximately 5 ha has been grown; an area of 1000 ha has been grown commercially for fibre use. Two harvest times have been used for fibre hemp. A “dry” harvest in August (sun dried and baled) or a “wet” harvest in September using maize choppers.

In Austria, 160 ha of hemp was grown during 1992–1995 for seed and fibre use. Yields of 6–14 odt/ha were achieved. There are some concerns about the handling of the harvested material, the problem being fibres wrapping around shafts, bearings, drums, etc.

2.3.18. Analysis. Hemp is considered an easy crop to produce with low demands for pesticides and fertilizer. Sowing is performed with standard drilling machines. Yields are relatively high compared with the inputs. As an annual crop hemp fits well into crop rotation where it may serve to reduce attacks by pests as it is not related to conventional crop species. Economic analysis from the Netherlands indicates a cost of 84 ECU/odt, but estimated storage costs are very high and could possibly be reduced.

2.4. Oilseed crops and crops for fermentation

Crops that are considered for both combustion and fermentation (like grain crops and sorghum) were treated earlier.

2.4.1. Oilseed rape (Brassica napus)

2.4.2. Achievements. Rape is without doubt the most widely grown energy crop in Europe. This is mainly due to the development of agricultural production of rape for food and fodder and the oil is relatively easy to use and to introduce into markets. The production areas described below are for all non-food purposes, which includes lubrication oils. As the crop production for food is very well known, this is not discussed.

The varieties used for food and fodder are low in glucosinolates and erucic acid, but this is not necessary if the crop is to be used for energy. The crop needs a high level of inputs, which makes one question its sustainability. The overall energy balance seems only slightly positive. There is a risk of considerable N₂O emission due to high N fertilization, which reduces the beneficial effect on the greenhouse balance from the oil production. If the straw is utilized for energy as well, the energy balance is improved.

In Germany 334 000 ha were grown in 1995 and this area is not expected to be extended due to the restrictions of the Blair House compromise in GATT. However, if the protein meal is combusted or fermented, then the restrictions no longer hold.

In France, 190 000 ha were grown in 1994 and 320 000 ha in 1995, while a decrease to 222 000 ha was observed in 1996. A global life cycle analysis (LCA) has been conducted in which the energy and carbon balances are well treated, while emissions are only qualitatively described. In the U.K., about 80 000 ha of rape is currently grown for non-food purposes and 200 t of biodiesel are produced annually by British Biodiesel.

In Denmark, about 40 000 ha is grown, but this is expected to decrease as the largest contractor for the seeds is retracting from the market due to a lack of political support. The major reason for farmers’ interest in the production has been the possibility of using man-
ure on the crop, which is highly regulated in Danish agriculture. Low-input systems for non-food rape production are being developed.

In Belgium, 7200 ha were grown in 1995. A new variety with increased seed yield and resistance to lodging (but with a slightly higher content of glucosinolates) is said to increase economic viability. In Austria 13 600 ha are grown. In Italy, 4700 ha is grown for energy purpose. The crop is considered a high input crop as it requires high N fertilization and has low resistance to pests.

In Finland, spring turnip rape (Brassica oleracea) is grown more commonly than conventional spring rape as it needs a shorter production period. In 1995 about 4000 ha were grown for non-food purposes. It has been calculated that if all Finnish tractors were to run on oil from spring turnip rape, 300 000 ha would need to be produced.

2.4.3. Analysis. Rape is a well known crop to European farmers and they are eager to cultivate it for non-food purposes. However, market regulations may soon reduce the possibilities. It is a high input crop and its environmental sustainability has been questioned. Recently, several life cycle analyses have been conducted, which included energy evaluations. These cast doubt on the overall performance of rape as an energy crop. If it is decided to intensify the use of rape for energy, further attempts should be made to improve the crop characteristics with respect to non-food uses.

The economic analysis of rape production indicates basic production costs between 140 and 250 ECU/odt of seeds. However, the lower price (calculated for Ireland) is because of very low machinery costs; in other countries production costs are over 200 ECU/ha. With prices of non-food rape seeds of about 150 ECU/odt, the production is not economic. In Austria, a negative annual gross margin of 144 ECU/ha is calculated. Despite the poor economics, large areas are produced throughout Europe. This is for several reasons. Farmers are basically interested in producing crops on their land and weed problems may occur if fallow set-aside is included in crop rotations. If returns are calculated on the basis of marginal costs (e.g. where farming machinery is owned for other purposes), the gross margin may not be negative. Rape is a well-known crop to farmers and there has been a well-established market for the non-food seeds. In Denmark, the possibility of using manure has been the main argument. The production of an annual crop is not as risky within the CAP as the production of perennial crops.

2.4.4. Sunflower (Helianthus annuus)

2.4.5. Achievements. In Italy, 55 000 ha of sunflower is grown commercially for biodiesel production. The average seed yield is 1.7–2.4 odt/ha. The crop has lower demands for nitrogen and pesticides than rape. However, the oil has a high iodine number.

In Spain, 4400 ha was grown in 1993/1994 and about 36 000 ha in 1994/1995. The crop is mainly grown on rainfed areas and the expected yield is only about 0.6 odt/ha seeds. The planting density is varied according to the water availability and also the varieties are suited to different water regimes as the length of their growing season varies.

In Austria, 360 ha is grown commercially for non-food production. In total, 39 000 ha of sunflower were grown in 1994. The average yield is 2.6 odt/ha seed. Sunflower is harvested in September with a dry matter content of about 90%. Conventional grain production machinery is used.

2.4.6. Analysis. In central and southern Europe, sunflower may be an alternative to rape as a low input oil crop. However, the high iodine number should be looked at. It seems to be possible to breed for low-iodine varieties. In Austria, the basic production costs of seeds are calculated to be about 250 ECU/odt, which is comparable with the production costs of rape seed. However, in Spain costs are calculated to 343 ECU/odt due to the low expected yields.

2.4.7. Sugar beet (Beta vulgaris)

2.4.8. Achievements. Sugar beet is a well-established crop, which means that the farmers have the cultivation knowledge for the crop. In France, 6250 ha of sugar beet were grown for energy purposes (ethanol/E18E) in 1995. Yields of 70 t beets/ha is harvested on a national average.

2.4.9. Analysis. Cultivation of sugar beets for energy purposes is not expected to be different from the production for sugar extraction. Accordingly, no breeding has been targeted for energy use. The cost of ethanol from sugar beets in France is calculated to be 48.7 ECU/hl (hl is 100 l). In Spain, the raw material cost of sugar beet is calculated to be
20.9 ECU/hl, to which processing costs should be added.

Calculations made in Spain on energy aspects on the full chain from field to ethanol, show an energy balance of 0.66. This means that the amount of energy obtained is less than the energy consumed in the production and processing.

2.5. Economics of energy crop production

2.5.1. Overview of energy crop production data. SRC mainly concerns willow but also includes poplar and eucalyptus from some countries. For Miscanthus, two concepts are calculated in the Danish report: autumn/winter harvest of wet chips and April harvest of dry straw. This gives large differences in yield, fertilizer requirement and costs of harvest, storage and transport. In The Netherlands, two different calculations are also given, based on the information from two different institutions. SRC calculations are based on both direct delivery of chips and on storage of whole stems. Ranges from all calculations are included in Table 2.

2.5.2. Feasibility of energy crop production. In Sweden, the basic production costs of willow are reported to be 3.64 ECU/GJ (excluding grants), while the market price of similar biomass delivered to district heating plants is 2.0–4.0 ECU/GJ, with an average of 3.7 ECU/GJ. The market price of coal to the industry and non-industrial users is, respectively, 4.3 and 7.5 ECU/GJ, while for light oil market prices are 6.1 ECU/GJ (industry) and 9.8 ECU/GJ (others). For non-industrial users, the general energy and environment taxes are 5.82 ECU/GJ for coal and 5.56 ECU/GJ for gas oil. Thus, biomass is made feasible by the raised tax level for fossil fuels. In addition, grants are available for willow plantations.

In France, calculated production prices for Miscanthus and winter rye are 4 ECU/GJ and for willow 4.8 ECU/GJ, while the market price for coal amounts to 3 ECU/GJ for the industry and 6.5 ECU/GJ for private households. Solid fuel energy crops are at an early development stage in France, but considering these price levels, the gap between energy crops and fossil fuels is not as big as in many other countries. However, according to French ADEME, the latter is of less importance for France; to make energy crops feasible the investment costs for biomass fuelled boilers should be reduced by 50%. Liquid biofuels are much more favoured in France since esters and ethanol have high tax exemptions, of, respectively, 9 and 13 ECU/GJ (35 ECU/hl and

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**Table 2. Analysis of energy crop production costs, where data from more than two countries is available. Costs in ECU/ha/yr. Net costs are expressed in ECU/odt. Land rental and profit for the farmer are not included.**

<table>
<thead>
<tr>
<th>Energy crop</th>
<th>SRC</th>
<th>Miscanthus</th>
<th>Rape</th>
</tr>
</thead>
<tbody>
<tr>
<td>Preconditions</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Yield (odt/yr as a mean of the crop lifetime)</td>
<td>7 (FR)–12 (U.K., BE, IR)</td>
<td>9 (DK)–20 (U.K.)</td>
<td>2.5 (AU)–3( BE, IR)</td>
</tr>
<tr>
<td>At a dry matter % of Lifetime (yrs)</td>
<td>45 (U.K.)–75 (NL)</td>
<td>45 (DK. U.K.)–85 (NL)*</td>
<td>86 (DK)–91 (AU, BE)</td>
</tr>
<tr>
<td>Max yield from year no (only perennials)</td>
<td>3 (DK)–10 (U.K.)</td>
<td>1 (U.K.)–6 (NL)</td>
<td></td>
</tr>
<tr>
<td>Harvest intervals (years, only perennials)</td>
<td>3 (U.K., AU)–10 (FR)</td>
<td>1</td>
<td>—</td>
</tr>
<tr>
<td>Costs</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Crop establishment (depreciated over crop lifetime)</td>
<td>79 (BE)–291 (IR)</td>
<td>32 (NL)–977 (U.K.)</td>
<td>138 (BE)–160 (IR, DK)</td>
</tr>
<tr>
<td>Fertilisation</td>
<td>10 (FR)–157 (U.K.)</td>
<td>46 (BE)–178 (DK)</td>
<td>120 (BE)–218 (LPK)</td>
</tr>
<tr>
<td>Plant protection and weeds</td>
<td>10 (SW)–89 (NL)</td>
<td>0 (NL)–20 (U.K.)</td>
<td>95 (DK)–168 (BE)</td>
</tr>
<tr>
<td>Harvest</td>
<td>120 (IRL)–296 (U.K.)</td>
<td>141 (DK)–276 (NL)</td>
<td>171 (BE)–200 (DK)</td>
</tr>
<tr>
<td>Storage</td>
<td>0 (S, FR, DK)–188 (U.K.)</td>
<td>0 (BE, DK)–121 (U.K.)</td>
<td>0</td>
</tr>
<tr>
<td>Transport (50 km)</td>
<td>79 (BE)–150 (FR)</td>
<td>64 (U.K.)–233 (DK)</td>
<td>9 (IR)–20 (BE)</td>
</tr>
<tr>
<td>Field clearing of perennials (depreciated over crop lifetime)</td>
<td>4 (U.K.)–30 (FR)</td>
<td>2 (U.K.)–164 (NL)</td>
<td></td>
</tr>
<tr>
<td>Energy crop grants per ha</td>
<td>0 (most)–30 (FR, U.K., S)</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Net costs (ECU/odt)</td>
<td>38 (BE)–86 (U.K.)</td>
<td>73 (U.K.)</td>
<td>140 (IR)–250 (DK)</td>
</tr>
</tbody>
</table>

*Depending on harvest time.
*Depending on density.
1 ECU = $1.15 (1996).
50 ECU/hi). Currently, the sugar beet sector is more efficient in the production of bioethanol than the wheat sector in France.

In Austria, the gross margin of most energy crops is negative when grants are not included. Higher yields with lower costs should improve this situation. Without compensation measures, the gross margin for biodiesel production amounts to 115–144 ECU/ha/yr negative (3–4 ECU/GJ biodiesel) and for sunflower 180–210 ECU/ha/yr negative (4–6 ECU/GJ). The gross margin for energy grain is 123 ECU/ha/yr negative and for poplar as energy crop 1750 ECU/ha/yr negative. To make biodiesel production economic in Austria, the government established a tax exemption for 100% biodiesel of 0.28 ECU/l or about 7 ECU/GJ.

In the U.K., total costs per ha per year (excluding grants) are 1064 ECU for willow, 1467 for Miscanthus and 633 ECU for RCG. Expressed in ECU/GJ, the costs are 5 ECU/GJ for willow, 4 ECU/GJ for Miscanthus and 3.5 ECU/GJ for RCG. The market price of coal in the U.K. is 1.25 ECU/GJ, while oil costs 2.4 ECU/GJ in the U.K.. Thus, financial incentives are needed to make energy crops feasible in the U.K..

In Germany, some preliminary calculations on Miscanthus show that production costs inclusive of farmer profit are in the range of 4–11 ECU/GJ, depending on the yield level. Reported annual costs of poplar production are 640 ECU/ha, or 4 ECU/GJ (at 10 odt/ha and 16 GJ/odt). Neither solid energy crops nor biofuels are competitive with fossil fuels without incentives in Germany. For more information see Section 4.

In the Netherlands, basic production costs of 5 ECU/GJ were reported for willow (inclusive land rental) and hemp, while for Miscanthus 3 ECU/GJ was mentioned. In more recent calculations, in which land rental and sufficient income for the farmer are incorporated, minimum costs of 7 ECU/GJ for Miscanthus have been calculated. These costs must be compared with the cost of coal, which is at the level of 2 ECU/GJ at the gate of big power utilities in the Netherlands. With the recently introduced energy tax in the Netherlands, willow might just about break even, while the production of Miscanthus with the inclusion of land rental and farmers income is unfeasible without grants or other incentives.

In Denmark, legislative and tax regulations have made energy use of existing biomass resources such as straw and wood chips feasible. Current mean market prices are 4.7 ECU/GJ for wood chips and 4.0 ECU/GJ for straw at the energy plant gate. The price of coal for power production is about 1.1 ECU/GJ, while it is about 7 ECU/GJ for heating purposes. The price of fuel oil is about 12.5 ECU/GJ for heating. Basic production costs of willow are calculated at 4.4 ECU/GJ for direct delivery of wet chips during winter and at 4.7 ECU/GJ for the storage and delivery of drier whole stems. Similar costs for Miscanthus are estimated (3.8 ECU/GJ for the storage and delivery of dry big bales) while the cost of wet chips delivered directly from field to plant during the winter is estimated to be 2.9 ECU/GJ. Costs of production, storage and delivery of winter rye is calculated at 4.1 ECU/GJ. Apparently, energy crops can compete with biomass residues, but as the future of the set-aside regulation is uncertain, the establishment of perennial crops in Denmark has stopped. Combustion of grain crops in large plants is not allowed and only some demonstration projects which have obtained exemption are running.

It appears that where neither land rental (assuming set-aside land is used) nor profit for the farmer are included in the economic calculations, energy crops are in some cases able to compete with other biomass resources and fossil fuels at the current national tax levels. However, to overcome the barriers at the farming level, the growing of energy crops should be awarded a gross margin comparable with conventional agricultural products. Therefore, long-term stability for energy crops within the CAP is needed and farmers’ profits must be improved by one or more of the following options: cost reduction in energy crop production; fossil fuel taxes; combined production of biomass for energy and high value plant fractions; or to improve ground water quality.

2.6. Conclusions and recommendations for the production of energy crops

(1) A large number of crops have been investigated for their potential as energy crops in Europe. However, only a few have reached beyond the stage of R&D and have become commercialized and grown on larger areas. These examples exist due to the political and
financial support given by some countries and they have provided valuable information on the future demands for the implementation of energy crops in European agriculture. The main examples of large-scale commercial energy crop production are the production of oilseed crops for biodiesel in France, Germany, Austria and Italy and the production of willow for heat and power in Sweden. A basic distinction between these examples is that liquid fuel crops such as rape and sunflower are well-known crops in agriculture due to their use for food and cattle feed purposes, while the production of willow as an agricultural crop has to be developed in all aspects from breeding to harvesting methods.

(2) The crops investigated are suited to different climatic conditions throughout Europe. Crops like Cynara, sorghum and eucalyptus are only grown in the most southern parts of Europe. On the other hand, RCG is the crop best adapted to the cold climate of Finland and northern Sweden, while willow and rape can be grown in most countries of northern Europe. Miscanthus is grown throughout the more central parts of Europe, covering, however, regions as far apart as Denmark and Sicily.

(3) Very high yields of 30–40 odt/ha have been registered for crops like sorghum, Miscanthus and Arundo donax in central and southern Europe, but this is only measured in small research plots and has often required irrigation. On the other hand, in Sweden, the current net yield of willow under commercial conditions is estimated to be 8–10 odt/ha and in many cases even less. This indicates the wide range within which the realistic yield level of solid energy crops in Europe can be found.

(4) The yield level can be influenced by the time of harvest. With RCG and Miscanthus, the full biological yield can be harvested in autumn, or harvest can take place in spring when the leaves are lost. By spring harvest yield is decreased by 25–50%, but the fuel quality is increased since the biomass is dry and can easily be stored and organic matter and nutrients are recycled to the soil. This means that the optimal production strategy, apart from the yield level, also depends on the fuel requirements of the energy sector and on ecological considerations.

(5) The first commercial willow plantations in Sweden have now been established and an evaluation has yielded the following conclusions: good advice to farmers is essential; weed treatment techniques need further development; good and cheap establishment is essential for the long-term production capacity and for the economics; crop water requirement is high and often water availability is the limiting factor for production; heterogeneity of fields has a strong influence on yield; fertilization below recommended levels has decreased yield by about 20%; the fertilizer effect is strongly dependent on successful weed treatment; and the highest yields have been obtained on organic soils.

(6) Economic calculations on energy crop production have been collected under different national conditions such as yield and cost levels. The basic costs of production and delivery to a plant for solid fuel crops are calculated to be in the range of 34–86 ECU/odt, with the Swedish calculation of 59 ECU/odt willow as the best documented. In Spain, it has been calculated that the costs of producing Cynara under non-irrigated conditions can be as low as 24 ECU/odt. These costs can be compared with current market prices of biomass residues like forest wood chips, the price of which in Sweden is 32–68 ECU/odt and in Denmark is about 80 ECU/odt. The mean market price of straw in Denmark is about 70 ECU/odt. The free market price of fossil fuels is lower than these prices of biomass when expressed in costs per unit of energy (ECU/GJ). However, in some countries taxes on fossil fuels have levelled the prices.

(7) The above cost ranges indicate that basic production costs of energy crops, in some cases, can compete with existing biomass market prices and with fossil fuels. However, land rental and profit for the farmer are not included in the calculations. Land rental is currently more or less covered by the set-aside regulation, but this may not be the case in the future. This uncertainty is a major barrier to the production of perennial energy crops. There is a need for long-term stability with regard to the status of energy crops in the Common Agricultural Policy. Profit for the farmer can be created by fiscal regulations but may also be achieved by cost reductions in the bioenergy chain. Another way of increasing feasibility is by combined production, where a high value fraction of the crop can be extracted for other purposes. The co-production of high-quality ground water due to
low levels of nitrate leaching and pesticide use could also be a valuable output from energy crop production.

(8) Even though rape production for energy use is not economic according to standard economic calculations, considerable rape production for biodiesel occurs throughout Europe. This has several rationales, but basically indicates that European farmers do have interest in producing crops for energy purposes. However, the instability of the CAP regulations is less of a problem with an annual crop such as rape, it has a well established market and uses well-known technology. These conditions are not met by most energy crops and this makes them less attractive to farmers.

(9) Cost reductions in energy crops have already taken place for rape, sunflower and energy grain, as they have been developed for food purposes and only small adaptations and further cost reductions are expected when they are used for energy. Cost reduction is one of the major ongoing R&D tasks for new energy crops and there seem to be good opportunities for reduction by the development of higher yields. The results willow in Sweden are illustrative: by combining programs of fundamental biological and environmental R&D and more applied programmes as well, high-yielding clones with good tolerance to frost, pest and rust have been developed. The technical development led to a reduction of the plantation costs by 50% from 1200 ECU in 1990 to 600 ECU in 1995. A similar development has started for Miscanthus where breeding has been initiated and a low cost establishment method has been tested which indicates that costs can be reduced from 4-5000 ECU/ha to less than 1000 ECU/ha. Costs for harvest and storage have also been reduced for willow in Sweden and need to be addressed in the case of other new crops.

(10) The use of energy crops will save fossil fuel resources and reduce the emission of the greenhouse gas CO₂. It is most likely that the production of energy crops itself can be environmentally friendly, due to the low demands for pesticide use (as the energy industry does not need a visually attractive product). Furthermore, several of the potential energy crops are perennial, which reduces the risks of soil erosion, nitrate leaching and humus degradation. Energy crops could furthermore be a valuable tool for the safe conversion of waste-water and sludge into useful biomass. However, water seems to be the major limiting factor to energy crop production, especially in southern Europe, but also in countries such as Sweden and Denmark. Perennial crops with a long growing season have the highest water use. As water, like energy, is a limited resource, the best use of available water resources should be analysed. This includes: evaluation of crop water use efficiencies (e.g. higher biomass production per unit of water used in C4 compared with C3 crops); suitable growing strategies of crops (e.g. Cynara is adapted to areas with a dry summer period); and regional analysis of total water balances with different land uses.

(11) To summarize, the major bottlenecks and gaps of knowledge to be focused on in further R&D on energy crop production are: breeding R&D in order to develop better adapted plant material with low input production and to maximize fuel quality; low-cost establishment of perennial crops; efficient and environmentally friendly weed treatment; energy crops' water demand and its implications for productivity and ground water recharge; possibilities for use of wastewater, sludge and/or ashes in energy crops; the influence factors such as genotype, harvest time, fertilization and climate on energy crop quality for conversion; and finally, effective dissemination of knowledge on new crops to farmers is a key issue for the successful introduction of new crops in agriculture.

3. HARVESTING AND PROCESSING

3.1. Introduction

Harvesting and processing (pre-treatment) covers all necessary steps to make the grown energy crop ready for conversion into electricity, heat or a liquid transport fuel. The following steps are distinguished: harvesting (mowing, cutting); packaging (baling, bundling); densification (briquetting, pelletizing); transport (small scale, large scale); storage and drying (outdoor, indoor, natural, artificial drying); and comminution (chipping, powder production).

From an overview literature study on pre-treatment of energy crops for electricity/heat production (BTG, 1995), it was concluded that the lowest economic costs and greenhouse emissions are achieved with dry-harvested and
easily-chipped energy crops. This would favour energy crops which can be harvested dry (moisture content below 20%) like Miscanthus or RCG. However, the choice for a specific energy crop also depends on many other factors like the year round availability, suitability for specific thermal conversion routes and crop production costs. Nevertheless, from the report it was made clear that the harvesting and processing costs can be significant and very site specific as well, as they may range from roughly 30 to 150 ECU/odt. It is clear that optimization of the pre-treatment offers significant cost reduction potential.

3.2. Woody energy crops

3.2.1. SRC (willow and poplar)

3.2.2. Achievements. The status of the harvesting procedure varies throughout Europe: in countries with small plantations, such as the Netherlands and Ireland, the harvesting process is in the earliest stages. Where larger plantations exist (U.K.) the process is generally in the demonstration phase, while in Sweden and Denmark it is now considered to be commercial.

3.2.3. Harvesters. Many countries have developed prototype harvesters, such as the Nicholson and Loughry trailer harvester developed in the U.K., the German prototype developed at the University of Göttingen and the Swedish Empire 2000 stick harvester. However, there are some machines which are commercially available such as the Austoft 7700 self propelled harvester (sugar cane harvester), the self propelled Claas Jaguar 695 with a specially developed Salix header, the Fröbbesta trailed harvester, John Deere, Salix Maskiner, Swedish Bender 85 kW, Bender 125 kW and the Kemper Header (which attaches to a conventional forage harvester and HE all-rounder). The harvesting rate of the machines is variable and dependent on the trial conditions.

Harvesting systems of SRC have different energy consumption figures depending on the techniques used and the power of the tractors involved. In general, it can be concluded that self propelled cut and chip harvesters are very fast and have a high energy demand. Stick harvesters have a lower energy consumption, whilst manual harvesting will have the lowest consumption, but also the lowest harvesting rate.

3.2.4. Pre-treatment machinery (chipping, briquetting, pelletizing). The most common pre-treatment method for SRC is direct chipping. Forestry based mobile chippers are commercially available in most countries and many have been developed in Sweden. In Sweden, biomass, mainly from forestry, is briquetted and pelletized commercially. This process can take place at all scales; from small farm projects to large-scale commercial plants. There are 30 high capacity plants in Sweden, which each have a processing capacity of between 10–65 000 t/yr. Total briquettes, pellets and powder capacity in Sweden is over one million tonnes per year, of which 500 000 t/yr is for the production of pellets. Briquettes are mainly used in heating plants in the range of 1–10 MWth.

3.2.5. Drying and storage. Drying of SRC can be performed with the following morphologies: chips (high piles, thin layers, natural drying, forced ventilation); sticks; and trunks.

3.2.6. Chips. The high resistance to air flow in chip piles limits natural drying and thus reduces transpiration of heat and moisture. Even when wood chips are stored in thin layers, natural ventilation remains poor. The drying location depends on the logistics of the supply. If the chips are transported and used directly after harvesting no drying is necessary; otherwise the chips are usually dried at the farm.

In Austria, some novel methods are being considered and tested. One method depends on the drying effect of thin layers of chips on a concrete or asphalt floor. The layer of chips is less than 1 m thick, but the thickness depends on the moisture content. From time to time the layer of chips are turned over to assist drying. When the chips are dry enough to be stored, they are piled up.

In the U.K., extensive research has been undertaken into the drying and storage of wood chips from forest residues and SRC. As part of this comprehensive programme, mathematical modelling has been carried out on the behaviour of woodchip piles. This has been incorporated into a model which can accommodate the variables of size, moisture content and weather. In recent chip storage experiments in the U.K. a 400 t pile was constructed. This was cooled and ventilated by ambient air. Over an eight month storage period there was a 6–10% dry matter loss.
3.2.7. Solar drying. The use of solar energy for drying forestry woodchips is also mentioned by Austria and may be used for SRC. The south side of the storage barn roof is adapted as a solar energy collector. It is covered with panels of glass or with cheaper transparent plastic roof material. The rafters of the roof are covered with black boards in front of the transparent panels. In channels, the air is heated by the collected sunlight. The warm air is sucked off by fans installed in the floor of a drying chamber. The floor of the drying chamber is a fine mesh grid which allows the circulation of the warm air underneath the pile, encouraging the drying of chips.

3.2.8. No storage and drying of chips. In Sweden, Salix chips are not stored because it is too expensive. Instead the fuel is transferred directly to the power/heat plant, where it is co-combusted with forest residues.

3.2.9. Stick drying. Sticks do not deteriorate in the same way as chips and left out in the open over the summer they will dry substantially. This means that they can be left on the corner of the field or headland without the need for transportation to the farm or the construction of a storage building. The moisture content of Salix is reduced from about 50% to an average of 30% during storage. Dry matter losses are approximately 7–10%. However, further drying may still be necessary once the wood has been chipped. The big disadvantage of stick harvesting is the double handling time involved, the lack of efficient harvesting systems and the reduced bulk density for transportation purposes, resulting in high costs.

3.2.10. Trunk drying. Trunks (2–4 m lengths) are sometimes thought to be the best solution to drying SRC wood because the bulk density is higher as compared with chips and sticks and storage problems are reduced because air can flow through the trunk pile and reduce heating, spore formation (fungi) and dry matter loss. In recent experiments carried out on the unventilated storage of trunks, over an 8 month period, the dry loss was 6–12%, similar to that in ventilated chip piles. Trunk drying in high piles of up to 9 m is a commercial drying method used in the pulp industry. The upper layer of 1 m is used as a cover layer, while the wood is dried by natural ventilation.

3.2.11 Energy consumption for artificial drying. As reported from Sweden, the consumption of energy in conventional artificial drying methods varies between 2.8 and 4.5 MJ/kg of water evaporated. There are other techniques which can be employed with lower energy consumption figures, for instance steam drying or dryers with heat pumps.

3.2.12 Environmental impact. The harvesting, packaging and transport of coppice wood takes place in winter and so the impact and importance of environmental issues is often a reflection of the weather during that period. For example, in Scandinavian countries, the ground is frozen during harvesting. This means that the impact of the 7–16 t harvesting vehicle and additional traffic will be minimal. The advantage of SRC is that the passage of machinery is minimal in comparison with normal row crops. In countries like the U.K., Ireland and the Benelux countries, the problem of soil damage is greater than in other parts of Europe since the winters are wet and cause muddy ground conditions. Under these conditions, heavy machinery can cause compaction and permanent soil damage. Preventive measures such as the use of flotation or wide tyres are already used. The extra burden on rural roads may also cause concern. In Ireland it has been calculated that any extra burden can be reduced by 50% by using a double axled vehicle.

The calculated energy output/input ratio for willow chips (incl. 30 km transport) for Sweden is about 17. Importance factors for the input/output ratio in energy terms are: the amount of fertilizer used; the average net yield achieved with this amount of fertilizer; and the size of material loss in the process (see Table 3).

3.2.13 Costs

Analysis. Harvesting and pre-treatment machinery for SRC is commercially available. Research is aimed at optimization of drying and storage methods. Most experience in willow harvesting and processing is without doubt available in Sweden. The most common pre-treatment method for SRC is direct chipping. Forestry based mobile chippers are commercially available in most countries and many have been developed in Sweden.

The moisture content for all types of SRC at harvest is typically about 50%. For efficient combustion or gasification of wood, the moisture content must be reduced to 15–25% whilst
minimizing the loss of dry matter. However, when combusted in a plant with a smoke condensing unit, a higher moisture content (for example 50%) can be accepted. In principle, drying can be performed in chipped form, sticks or trunks.

Many experiments have taken place throughout Europe regarding the storage of willow chips under different conditions. The results show the following potential problems: heating, rotting due to high moisture levels and spore build-up. Trunk drying might be the best option if storage for longer periods is needed. Trunks drying in high piles of up to 9 m is a commercially proven drying method in the pulp industry. The upper layer of 1 m is used as cover layer, while the wood is dried by natural ventilation.

The best method is a function of the transport distance, handling costs, storage capacity, climatic conditions and logistical planning of the users. A route often followed in Sweden is co-combustion of willow SRC with other fuels, thereby minimizing the influence of the calorific value of wet willow.

3.2.14. Eucalyptus. Eucalyptus is currently grown in France, Greece and Portugal, but is not used for energy purposes. Moisture content at harvest is 50–60%. The use of eucalyptus in the pulp industry in France is in the demonstration phase. It is currently harvested manually in France. A harvest demonstration machine will be available and operational by 1997. From the other countries no experience with harvesting and processing is reported.

3.3. Herbaceous energy crops

3.3.1. Miscanthus

3.3.2. Achievements. The moisture content of Miscanthus at harvest depends on the harvesting season. In most countries Miscanthus is harvested in spring when the vegetation matter is at its driest and can be stored without the risk of mould or fungal attack. The moisture content at this time is usually between 15–25%, although levels have been known to reach up to 50% in Austria and Greece. Miscanthus is harvested in autumn since it has environmental benefits, such as reducing soil compaction, but the moisture content of the grass is higher (up to 66%).

3.3.3. Harvesting and pre-treatment. There are currently several different Miscanthus harvesting methods which are being investigated, tested or/and demonstrated and these are as follows.

3.3.4. Forage harvesting. A normal forage harvester can be used to harvest Miscanthus. The harvested crop can be easily baled or chopped with a maize header or the specially adapted Kemper Head. Harvesting demonstrations of this equipment have taken place in the U.K., Denmark, the Netherlands, Germany and Austria.

3.3.5. Mowing. In Denmark, mowing is carried out with a conventional mower with an effective crimper. In the Netherlands, Germany, Denmark and the U.K., Miscanthus is also mown by a swath mower (modified for tough stalks) and baled. This process can be carried out as a one or two pass operation. A problem with the first method is that a lot of tramp is picked up with the fuel. When mowing is performed in two steps, a higher loss can occur. Claas (Germany) has recently developed a machine which can cut and bale Miscanthus in a one-pass operation. In the Netherlands, three machines have been specially tested and slightly modified, including a Vicon swath mower and a Vicon self-propelled harvester (see Fig. 2.

3.3.6. Baling. Once the crop has been cut with a swath mower it can be baled with a conventional or high pressure baler and a variety of bale sizes and shapes can be produced. In Denmark 1500 big balers, of which 800 are Hesston 4800 or 4900, are in commercial use.

3.3.7. Bundling. In the Netherlands and Denmark the bundling method has been tested and provided the best results for harvesting whole Miscanthus stems. Two reed harvesters from Agostini and Seiga were tested. The tests indicated that the machines need to be adapted for the larger and stiffer Miscanthus stems. In order to minimize labour costs, large bundles must be created to maximize handling efficiency.

3.3.8. Pelletizing. Miscanthus can be also be pelletized. Higher energy efficiencies can be achieved in thermal conversion than with bales or chips and they are more economic to
transport because of their higher bulk density. However, the process is very expensive and requires a lot of energy. Miscanthus is not very suitable for pelletizing because of its mechanical properties.

3.3.9. Transport. In many countries the transportation of Miscanthus has not been considered because of the early stage of development of the industry. In the U.K. it is anticipated that silage trailers will be used for the chopped material or that flat bed trailers will be used to transport bales. If chips are being transported, they will be loaded into the trailer by the spout of the harvester and unloaded by tipping. Bales can be picked up and transported by tractor or fastrac baler collector.

The biomass material (bales or chopped material) is transported from the farm to the storage facility or the use plant by commercial transport. Chips of Miscanthus are loaded by a front end loader with a bucket attachment, or with a shovel or fork lift and then transported by 90 m³ articulated lorries (U.K.), semi-trailer (Holland) or lorry (Denmark).

3.3.10. Drying and storage. Following a good winter and a spring harvest, Miscanthus is dry enough to store without further drying. However, in poorer years or following an autumn harvest, the grass will be wet and will require drying before storage. In the U.K., it has been estimated that for storage over 6 months, a moisture content of less than 20% is required. Chopped material and whole stems can be dried artificially or naturally in piles; whole stem bundles allow natural drying from as high as 80% moisture contents. Drying bales is more difficult if the moisture content exceeds 20%; the storage time will have to be limited to prevent moulding. Drying of compact bales is almost impossible.

A drying test performed at the Research Centre, Bygholm (Denmark), showed that if harvested in autumn, loose, chopped Miscanthus can be dried in a conventional platform drier with non-heated air. The moisture content was reduced from 59 to 17.5% and the energy consumption was 4.0 MJ per kg of dry matter or 3.2 MJ/kg of evaporated water. The energy content of the crop is about 17 MJ/kg of dry matter, which again demonstrates that drying is a rather energy consuming process.

Another option is to store the crop outdoors in a naturally ventilated pile. A test with this type of store (Denmark) showed that it is possible to store Miscanthus which has been harvested in autumn/winter and stored until spring/summer, but minor dry matter losses were incurred. After an initial moisture content of 63% and storage period of
178 days the storage loss was 5% and the moisture content was reduced to 51%.

In the Netherlands, experiments have taken place on the drying of Miscanthus in piles under a plastic cover. In these conditions the piles can be left in the field and constructed in such a way that some drying by natural ventilation is possible. In Germany, Miscanthus material is stored for about two months. Chopped material is stored in flat boxes (156 m³) and placed on top of each other. Few cost calculations for storing and drying Miscanthus have been submitted. In the U.K. it has been calculated that it will cost 19 ECU/t to dry Miscanthus in a barn.

3.3.11. Harvesting window. There is much debate about the best time to harvest Miscanthus. A producers' decision tends to be primarily influenced by the moisture content and yield of the crop, but there are also important environmental concerns. The best time to harvest, in crop terms, is the end of winter (see above) but soils tend to be wet and muddy at this time and the use of heavy machinery may damage the soil. It may be better to harvest a crop in autumn when the soils are dry, but the moisture content is then higher and creates a problem for drying. Preventative measures to protect the soil from damage like flotation tyres, caterpillar tracks, etc. can be taken. An advantage of harvesting in autumn is that considerably higher yields can be achieved.

3.3.12. Environment. In the packaging process (chipping, baling etc.) and during storage there are concerns about spore release which may affect human health. In Germany, it has been calculated that the highest environmental costs are for pelletizing and the lowest are for cutting and pressing. Carbon dioxide emissions from transportation depend on the bulk density of the transported material, which reflects the harvesting and processing methods applied.

3.3.13. Economics

3.3.14. Packaging. The only packaging process which has been considered is baling, where the energy consumption is 26.1 MJ/odt (U.K. calculation). Pelletizing consumes far too much energy to be economic.

3.3.15. Analysis. The technology of harvesting and processing of Miscanthus is not fully developed yet. For supply chains this is mostly due to technical bottlenecks. Miscanthus can be harvested dry (15–20% moisture) in early springtime and can be stored without risks of moulding or fungal attacks, but depending on the local climate conditions, the harvest window can be very small. If the crop is harvested in autumn, a considerably higher yield can be achieved, but the moisture content will be as high as 60–70%, resulting in a low calorific value of the crop.

Two routes seem to be followed with respect to harvesting and processing of Miscanthus: (1) cutting, transport and baling afterwards; or (2) cutting and baling in one step. The first option has the disadvantage of transporting loose material, resulting in high transport costs. The second method needs further development since dirty and wet material is baled as well at present. Modifications of baling equipment originally designed for straw baling seems to be necessary. Here lies some interesting development work for the manufacturers of harvesting and pre-treatment equipment.

3.3.16. Reed canary grass (RCG)

3.3.17. Achievements

Overview. There are RCG plantations in Finland, the U.K. and Sweden. The industry is most developed in Sweden, where two levels of development can be distinguished: large and small scale. For both scales, the grass is mown and baled. These bales are then transported by commercial transport to the power and/or heat plant, where eventually further comminution to powder can take place, as in the case of co-combustion in a 30 MWth powder fired district heating system.

In Finland, the anticipated end use of RCG is small scale heat production. The grass is cut and chipped with a forage harvester. The material is then transferred to a tractor and trailer, which take it to the storage site. Here it is mixed with bark or peat and transferred by peat lorry to the use plant. In the U.K., just a few small research plots exist which are harvested by hand.

3.3.18. Harvest window. It is reported that since RCG is more brittle, slippery, more difficult to handle than straw and breaks up easily leaving high mechanical losses, harvesting can be problematic. In Finland, harvest is very
precisely timed and must occur within one week after the final snow melt, this is when the moisture content is at its lowest; 10–15%. If the grass is left in the field it will dry further, but in wet weather it will reabsorb the moisture lost. When RCG is harvested in spring it is usually dry enough to store without further drying.

3.3.19. Harvesting. Established and commercial harvesting techniques can be used to cut RCG. The crop can be cut and chopped with a forage harvester or it can be mown by a mower conditioner or a self-propelled windrower (this worked very well in Sweden) and baled. Baling can be performed in round and in rectangular bales. The moisture content at harvest is 10–15% and the weight of the bales varies between 100 and 500 kg. All machinery is commercially available and many (thousands) of machines exist in Sweden and Finland. Bundling can also be considered as a form of packaging for RCG, but little information has been supplied for this review.

3.3.20. Transport. RCG is transported by trailer or balespike from the farm to the storage area. In Finland, the storage facility is often the nearest boggy area. Chip lorries are used to transport the chopped grass. They are loaded using a bucket attachment and unloaded by tipping. In Sweden, up to 1000 t of RCG in big bales is currently commercially marketed and co-combusted with straw. It is transported by tractor. The material is loaded by a standard crane mounted at the rear of the lorry. Bales have a bulk density of 130–160 kg dm/m³.

3.3.21. Drying and storage. In Sweden, several farmers and scientists have tried to store baled straw and grass outside. It appeared that it can be quite difficult. For large amounts (1000 t), a technique used in the U.K. and in Denmark is to build densely packed piles out of uniformly sized bales for storage. The pile of bales is so big that damage to the bales in the top layer is accepted and seen as a marginal loss. In Sweden, it is more difficult to preserve the quality of bales when they are stored outside. This is because heavy rain falls between July and December, as well as the occurrence of heavy storms. In Finland, experiments have taken place with storing material in covered piles, in the Agrofibre project. Stored RCG is assumed to last about 6 months. However, some stacks have successfully been stored for up to a year.

The typical Finnish stack is described as three bales laid horizontally, with two bales balanced on them and one bale on the top. The format of stack is easy to cover because it forms a natural slope for rain water and melting snow in spring. Still there is a need for some kind of isolation against the moisture coming from the ground. The yield from one hectare (6 t dm/ha) requires an area of about 25 m² for storage and a plastic or tarpaulin cover of about 45 m². In covered stacks the dry matter losses are approximately 2%.

3.3.22. Economics. Little economic data were submitted on storing and drying RCG: in the U.K., the cost of storage is 1.2 ECU/odt. In Finland, the cost is 19 ECU/t when storage takes place in a barn.

3.3.23. Analysis. RCG is seen as one of the promising crops in Finland, Sweden and the U.K.. It seems that established and commercially available harvesting techniques can be used for harvesting RCG. Like with Miscanthus, there is also a debate about the best time of year for harvesting: autumn or spring. One of the valuable advantages connected to spring harvested grass is that the crop will be very dry. Experience in Sweden indicates that generally it is possible to hold the dry matter content above 80% and that it often will be between 85 and 90%. The more specific the requirement for a particular dry matter content, the shorter the time period available for harvest. If the harvesting is performed earlier, during winter or very early spring the average dry matter content will be lower than that stated above. However, when harvested in the spring, it is at the end of the heating season, so the grass must be stored until the following autumn and winter. At the dry matter levels indicated, there should be no risk of moulding during the storage which would cause decay and risk of health problems.

3.3.24. Whole crop energy grain

3.3.25. Achievements

Overview. Triticale is grown as an energy crop in Austria and Denmark. In Denmark, large quantities are grown; 535 ha of energy grain were produced in 1995, of this area 375 ha were harvested as a whole crop and baled in big bales. The rest was harvested by combine. In total 4000 odt of big bales were produced and 500 odt of grain.

Harvesting. Cereals harvested for energy purposes are harvested as whole crop energy grain (the cereals grains with the straw). The
cereal crossbreed Triticale is the main interest in Austria. Because the moisture content of the cereal straw is very high and different from the moisture content of the grain, drying is necessary to prevent the energy crop from rotting.

Two major harvesting processing chains are distinguished:

1. the crop is windrowed (swath mown) and then the cut swath is dried on the field for some days, baled and transported to the storage area and then to the use plant by a commercial vehicle;

2. the crop is harvested by a combine harvester, the loose crop is then transported by a tractor and trailer to the storage area and then by commercial transport to the use plant.

The various harvesting methods are at different stages of development. Where the Triticale is mown with a windrower producing swaths, the technology is at a demonstration/commercial level. However, the direct harvesting method, in which the triticale is harvested and baled in one pass by a self-propelled machine, is currently in the research phase (Austria). In Austria only old (5 yr +) swath mowers are still in use, however there are many big balers in both Austria and Denmark which are less than 5 yr old.

Chopping. Chopping takes place directly if the crop is harvested by a forage harvester. The disadvantage is that the density is low and that the chopped crop is not easy to handle. Large volumes would thus be required for storage and transport. In Austria this process is still considered economic when transportation distances are short.

Baling. When the crop has been cut into swaths, it is left in the field for drying and baled. Standard-size bales are produced by commercial machinery. The bale size is dependent on the type of baler used. Baling can take place with a conventional baler, but more recently high-pressure balers were introduced. These are gradually replacing conventional balers. Square compact bales are easier to manipulate than conventional round bales and reduce storage space and transport costs. Current machinery can produce different bale sizes e.g. 1.2 x 1.3 m, 0.8 x 0.8 m and 1.2 x 0.6 m.

3.3.26. Pellets. In Austria, there are some stationary pelleting systems, but they are very expensive. Pellets are very compact and have a high bulk density, which means that they are easy to handle.

Drying and storage. The crop (moisture content at harvest 15–19%) dries very slowly and may require turning to dry effectively. Without turning the crop will be difficult to bale and the bales will be loosely packed. However, grain is lost during turning and the pros and cons must be weighed up. The duration of drying depends on stem thickness. When the crop is harvested and baled in one pass (the direct harvesting method) there may be a need for artificial drying. In Austria the bales are initially stored in a drying chamber and cold or warm dry air is blown through the stacked bales. However, it is difficult to reduce the moisture content of the material at the centre of the bale.

In contrast, the storage of big, dry, square cereal bales in Austria is an established process. In a dry summer it may be possible to store uncovered dry bales on the edge of the field for a short period of time. However, for long-term storage a cover is necessary. A simple roof is adequate, but storage inside a closed barn or similar building is preferable since there may be some problems with field mice and rats. The problem is not just a direct loss of grains, but also damage to the bale consistency. For example, damaged twine and the break-up of the bale by rodents makes handling of the energy crop nearly impossible. Another reported problem can be higher stack emissions when bales are contaminated by different animal residues.

Environment. Soil compaction from heavy machinery is an environmental issue that is highlighted. However, as the crop is harvested in the dry summer months this is not an important issue in any of the countries studied. There is a risk of fire in storage. This can be reduced by the use of fire retardant bricks and walls and by ensuring that all material is stored away from the heat generating plant.

Analysis. When considering cereal crops as fuel, species with a high straw yield and low inputs are the most interesting. Conventional harvesting technology from cereal production can be used. Germany mentioned the loss during harvesting and transportation as disadvantage of the combined harvesting machine. In addition, outgrowth of the grain can be a big problem when the crop is harvested too wet. The two-step harvesting method offers a dryer crop, but the high grain loss is a major
problem. Germany reported that new technologies are being developed for the production of pellets from whole grain crops. An expensive option is a recently developed self-driving compaction harvester from the firm Haimer.

3.3.27. Hemp

3.3.28. Achievements. Hemp has a very long tradition as a fibre crop, but the energy use of hemp is a new concept. Hemp was mentioned as a potential energy crop by the Netherlands and Austria. In the Netherlands it is grown on a commercial basis: 1000 ha are grown producing 7000–9000 odt of biomass, but the crop is not used for energy purposes. In addition, in France hemp is widely used in the paper industry. In Austria, 6–14 odt/ha/yr are produced. France reported that there is no interest in hemp as an energy crop since the yields are small (7–8 odt/ha).

3.3.29. Harvesting. The moisture content of hemp at harvest is 50–55%. In Austria, only a few harvesting tests were carried out to harvest the whole hemp crop for energy purposes. Hemp can be harvested by a forage harvester, but there are problems with the fibres wrapping around the machines' mechanisms and causing a lot of damage.

Hemp can be harvested directly using a maize or grass forage harvester, so there has been no need to develop specialist machinery. There are many commercial foragers used in Austria, the average age of machinery is approximately 10 yrs. The complete crop is harvested and chips (of variable length), bales or whole stem bundles are produced. The hemp plants can be harvested with a forage harvester and chipped directly when wet, or it can be cut with a swath mower and sun dried.

3.3.30. Drying and storage. It is stated by the countries that it will be necessary to dry hemp chips artificially. Austria stated that this process is similar to that used when drying and storing woodchips.

3.3.31. Transport. In reported tests, hemp is transferred from the field to the use plant directly. This distance is assumed to be between 5–20 km and standard tractor and trailer combinations are used. The trailers are hydraulically operated tipping trailers with high drop sides. The trailer is loaded by the adjustable spout of the harvester and unloaded by tipping.

3.3.32. Analysis. An advantage of hemp is that it is an annual crop, so it gives more flexibility to the farmer. Secondly, hemp it is not used for food production. The possible use as a drug is a disadvantage, however the species grown have low THC values. The current fibre market for hemp might be a more profit yielding activity than production of hemp for energy purposes. So far, insufficient data have been gathered to definitively rule out hemp as an energy crop. If hemp remains to be considered as a promising crop, improvements in the harvesting and processing might be necessary.

3.4. Oilseed crops

3.4.1. Rape seed oil

3.4.2. Achievements. Rape seed oil production is a well-established commercial activity in many countries; Denmark, Ireland, Germany, Belgium, France, Finland, Austria and the U.K.. The majority of rape seed oil is produced as food, but there is some conversion for the pharmaceutical industry and energetic purposes such as biodiesel production.

3.4.3. Harvesting. Two major techniques are used to harvest rape seed oil. Firstly, the crop can be mown and laid in swaths, left to dry in the field for 10–14 days and then threshed with a combine. This is the method used in Denmark. A more common technique is to harvest and thresh the crop in a one pass operation. Before harvest the crop must be dry. It is then harvested with a combine and the seeds are separated from the straw. This is the state-of-the-art method and many commercial machines exist in all the countries studied.

In some cases a chemical desiccant is sprayed onto the crop to avoid collecting any material which still contains chlorophyll. This is common practice in the U.K.. The rape must be delivered to the mills with a moisture content less than 9% and must contain no mould or fungi.

3.4.4. Transport. After harvesting by a combine, the seeds are directly transferred into a tractor and trailer. They are then transported to the local point of use, or an intermediate storage area. This is usually a distance of less than 10 km. The moisture content of the seeds is 10–15% and the bulk density is 610–740 kg/m³.

The seeds are transferred from the farm storage area to the crusher, oil mill or chemical plant by commercial lorries. This can be a distance of 150–200 km. The maximum lorry load varies between countries but is in the region of 28–40 t. In some countries the pro-
duct is also transported by rail or canal. The moisture content of the transported product is about 9%. Transport losses account for 1% of the seed transported.

3.4.5. Storage and drying. In countries where the weather is warm and dry, further drying is not necessary. However, in the case of bad weather conditions additional drying is necessary to prevent deterioration. Ordinary drying systems for cereal grains cannot be used, so special drying systems (e.g. continuous air flow dryer) for rape seeds and other small seeds have to be used.

Rape seed used in a large plant is first stored in an agricultural depot. The storage period can vary from some days to some months. The storage system is similar to the storage used for cereal grains. However, in some cases adaptations may be required because of the small size of the grain. In Germany the seeds are stored in cells or as flat storage (3–9 cm high), or in silos (25–30 m high). In Austria, emissions limits for particular air contaminants from the handling and treatment of cereal in the grain-silos and store rooms (Austrian Standard ONORM M9460) have been set. The product bulk density at time of storage is 740 kg/m³ wet basis (670 kg/m³ dry basis) and moisture content is 7–10%.

For turnip rape seed artificial drying in grain dryers is essential. Today these dryers are totally suitable for drying turnip rape seed. Storage of the seed takes place in silos which are located under the roof of the drier. The same silos are used to store grain. In the silos the bulk density is about 610 kg/m³ and the moisture content around 9% (wet basis).

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3.4.6. Economics. The cost of drying rape seed in Austria has been calculated as 13 ECU/odt, while in Finland it has been calculated as 9.7 ECU/odt. By Germany, it is reported that the dry matter content of rape seeds is about 86% at harvest. For storage a level of 91% is required. Drying costs are 18.5 ECU/t fresh matter.

3.4.7. Environment. Rape harvesting is an established practice for food production. Because the harvest takes place in the summer months there are few problems of soil compaction from agricultural or commercial vehicles. In Austria, it has been noted that the matted layer of vegetation at a low height can cause problems for human health with dust and seeds in the air. The seeds are very small and so leakage from the containers is easy and rape flowers have become a common sight along roadsides. There is a certain level of risk associated with a grain silo. Standard precautions should be taken and public access prevented.

3.4.8. Analysis. Harvesting and processing of rape seed is a commercially proven and fully developed technology. For further information, especially on the economic aspects, reference is made to Section 4.

3.4.9. Sunflowers. Sunflowers are grown for oil production in Spain and Austria. However, this is predominantly for food production and not for energy purposes. Since sunflower oil is not used for energy production in Europe and no promising developments were reported by the project partners, no attention is paid to sunflowers here. For interested readers reference is made to the country reports from Austria and Spain.

3.5. Sugar rich energy crops

3.5.1. Sweet sorghum

3.5.2. Achievements. Sweet sorghum is grown in Spain, Greece, France and Belgium. However, it is only used for energy purposes at a research scale in Belgium and France. The plots are small and the industry in these countries is still in the research phase. In France, a total area of 15 ha is dedicated to sweet sorghum for research purposes. The crop is harvested by a silage harvester and cut into small 5–10 cm pieces. These chips are then pressed into bales and loaded onto commercial transport.

Sweet sorghum is harvested between early September and late October. The moisture content of sorghum is very high (75–80%) and so the harvested product is crushed and left to dry. This reduces the moisture content to 35%. The leaves and panicle are removed from the crop and the stalk is chipped.

In France, sorghum harvesting is in the research phase and the method and technology available must be improved before demonstration projects can begin. Currently silage harvesters and straw balers are used, but only one especially designed prototype exists. In the Wallonian region of Belgium a new Italian prototype harvester and sugar cane harvesters are being tested on the sorghum plots. The bales of sorghum are then delivered to the use plant, where they undergo storage, fermentation, distillation and dehydration, over a period of 300 days.
Once sorghum is harvested it can be baled with a conventional straw baler. The bale size and density will thus reflect the type of baler used. In Belgium two major types are produced: round and cylindrical. Before baling, fibre sorghum must dry on the soil like a forage crop (moisture content has to decrease from 80% to 15–30). Sorghum is grown and harvested in a very dry climate and so soil compaction and erosion are not considered to be a problem.

3.5.3. Analysis. Harvesting and pre-treatment of sweet sorghum are commercially proven technologies; however, with respect to energy production, the experience is limited.

3.5.4.  

Sugar beet. Bioethanol production from sugar beet is commercialized in France in several countries sugar beet harvesting and processing is commercially proven.

3.5.5. Winter wheat

3.5.6. Achievements. In Europe, winter wheat is not considered as as promising energy crop. No commercial fuel ethanol production from wheat is currently taking place in Germany, but the option has been considered and some data was provided. Over the course of the year, the demand for the fuel would be fairly constant. Herein lies one of the advantages of wheat as an ethanol crop. It has good storage properties and storage is comparatively cheap. Winter wheat could therefore be a steady source of fuel throughout the year. A high protein content is not desired because it is linked to a low starch content and low grain yields, thus reducing the ethanol yield per hectare. The choice of an appropriate variety along with a proper amount and timing of nitrogen fertilization are the main agronomic measures that can be undertaken to obtain the desired low protein content in the grain. In order to increase the high starch content and the native enzyme content and activity, one could postpone the common harvesting date to several days or weeks after the full ripeness in order to promote outgrowth. However, at this late stage harvest losses become significant and the grain is no longer well suited for long-term storage.

Drying, storage and transport of winter wheat have been fully developed. A moisture content of 14% is appropriate for long-term storage. In Germany, winter wheat is harvested in the second half of July at full or dead ripeness, preferably at a moisture content of 16% or less.

3.5.7. Analysis. Harvesting and processing technology for winter wheat (and other grain crops) is fully developed and uses state-of-the-art technology since years due to grain production for the food market. When grown for energy purposes, some optimization of the fuel composition will be needed.

3.6. Conclusions and recommendations for harvesting and processing of energy crops.

(1) The most advanced energy crops, in commercial terms, are short rotation willow and poplar coppice. In Sweden, and Denmark SRC is being grown and used commercially in rural heating systems and CHP plants. These facilities are also able to utilize energy grasses such as Miscanthus, RCG and whole crop energy grain. In Sweden, and Denmark large demonstration plots of these crops exist, while in Finland smaller demonstration plots are in operation for energy purposes.

(2) In a local heating plant or small-scale power station one single crop does not have to be relied upon since several different biomass and fossil fuels can be used together. Scandinavian countries and Austria are successful in developing the energy crop industry, partly because they have a long history of using biomass from forest and agricultural residues and peat in small power stations, district heating and CHP plants. Novel crops can be slotted into this system.

(3) Miscanthus, RCG and willow/poplar coppice are novel crops and thus there are barriers of agricultural acceptance which must be overcome. In addition, new harvesting and processing technology must be developed. Other crops such as Triticale, sorghum, rape seed oil and hemp do not have the same problems because they are currently grown for non-energy purposes and can be cultivated and harvested by existing machinery. However, without policy support from the government their use for energy production will be limited.

(4) Where the development of energy crops is in the demonstration and commercial phases (Scandinavia, Austria etc.), a lot of information is available. Many of the systems described are up and running. In other countries, information about transport, storage and economics is more limited. In those cases, the information is speculative, taken from models, resource studies and educated assumptions. This makes it very difficult to
Table 4. Overview of selected major projects and plants aimed at use of energy crops for power and/or heat applications in Europe

<table>
<thead>
<tr>
<th>Energy crop</th>
<th>Area cultivated for energy purposes in Europe (ha)</th>
<th>Countries in which use of energy crop is most developed</th>
<th>Status</th>
<th>Selected examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Willow SRC</td>
<td>18,000</td>
<td>Sweden</td>
<td>Commercial</td>
<td>50 MW&lt;sub&gt;el&lt;/sub&gt;/110 MW&lt;sub&gt;th&lt;/sub&gt; CFB power and heat plant in Örebro, linked to a nearby 2000 ha willow plantation (maximum radius 30 km)</td>
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<td></td>
<td></td>
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<td></td>
<td>4 MW&lt;sub&gt;th&lt;/sub&gt; DH plant (VL energy, plant located near Lådöping; main fuels: straw, dry wood chips and willow)</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>In Sweden, thousands of tonnes of willow are co-combusted annually with other fuels, like coal, peat and forestry fuels</td>
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<tr>
<td></td>
<td>United Kingdom Demonstration</td>
<td></td>
<td></td>
<td>Three medium-scale demonstration power plants using gasification technology for power generation have been granted licences under the NFFO-programme (planned):</td>
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<td></td>
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<td></td>
<td>8.0 MW&lt;sub&gt;el&lt;/sub&gt; IGCC linked to a FB gasifier (Yorkshire Water Enterprises Ltd, Eggborough Power Station; also called the ARBRE project, received a grant from EC THERMIE programme as well)</td>
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<td></td>
<td></td>
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<td></td>
<td>5.5 MW&lt;sub&gt;el&lt;/sub&gt; gas engine (South Western Power Ltd, Eye Airfield Site A)</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>5.5 MW&lt;sub&gt;el&lt;/sub&gt; gas engine (South Western Power Ltd, North Wiltshire Biomass Power)</td>
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<tr>
<td></td>
<td>Italy</td>
<td></td>
<td>Commercial</td>
<td>100 kW&lt;sub&gt;th&lt;/sub&gt; SRC combustion plant (Brian Maggs Farm)</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td>Commercial</td>
<td>300 kW&lt;sub&gt;th&lt;/sub&gt; SRC combustion plant (Lionel Hill)</td>
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<td></td>
<td>Netherlands Demonstration</td>
<td></td>
<td>0.5 MW&lt;sub&gt;el&lt;/sub&gt;/7 MW&lt;sub&gt;th&lt;/sub&gt; combustion plant (NUON) linked to a 200 ha energy plantation (planned)</td>
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<tr>
<td></td>
<td>Denmark</td>
<td></td>
<td>Experimental</td>
<td>Combustion of 100 t of willow chips/SRC at a 5 MW&lt;sub&gt;th&lt;/sub&gt; DH-plant (Løkkens plant), winter 1995/1996</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Similar tests at a 3.6 MW&lt;sub&gt;th&lt;/sub&gt; DH plant (Andelselskabet Sdr. Felding plant), 1995</td>
</tr>
<tr>
<td></td>
<td>Ireland</td>
<td></td>
<td>Pilot—commercial</td>
<td>100 kW&lt;sub&gt;th&lt;/sub&gt;/200 skW&lt;sub&gt;el&lt;/sub&gt; CHP gasification unit using SRC willow chips from nearby test fields in Northern Ireland (Enniskillen)</td>
</tr>
<tr>
<td>Poplar</td>
<td>550 ha</td>
<td>Belgium</td>
<td>Pilot</td>
<td>150 kW&lt;sub&gt;el&lt;/sub&gt; down-draft gasifier coupled to a gas engine (Eurable and Walloon region), linked to a poplar SRC plantation</td>
</tr>
<tr>
<td>Reed Canary Grass</td>
<td>4050</td>
<td>Denmark</td>
<td>Experimental</td>
<td>150 t co-combustion tests in the 150 MW&lt;sub&gt;el&lt;/sub&gt; straw/coal fired Studstrup power plant (test duration: 10 h)</td>
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<td></td>
<td>17 t co-combustion test in the 80 MW&lt;sub&gt;el&lt;/sub&gt; Greenaa CFB plant for preliminary testing of pre-processing and feeding equipment</td>
</tr>
<tr>
<td>Energy grain (combustion)</td>
<td>520</td>
<td>Sweden</td>
<td>Research/demonstration</td>
<td>Tests in a 30 MW&lt;sub&gt;th&lt;/sub&gt; DH plant (55 t during 9 h)</td>
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<td></td>
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<td></td>
<td>2 MW&lt;sub&gt;el&lt;/sub&gt; wood chips fuelled DH plant fuelled with 200 t RCG (1995/1996; plant owned and operated by three farmers)</td>
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<tr>
<td></td>
<td>Austria</td>
<td></td>
<td>Demonstration</td>
<td>40 kW&lt;sub&gt;el&lt;/sub&gt; farm boiler (chopped</td>
</tr>
<tr>
<td></td>
<td>Germany</td>
<td></td>
<td>Experiments</td>
<td>Experiments in a 500 kW&lt;sub&gt;th&lt;/sub&gt; combustion unit; some gasification trials</td>
</tr>
<tr>
<td></td>
<td>Sweden</td>
<td></td>
<td>Research/demonstration</td>
<td>Tests in a 30 MW&lt;sub&gt;th&lt;/sub&gt; DH plant (55 t during 9 h)</td>
</tr>
<tr>
<td></td>
<td>Denmark</td>
<td></td>
<td>Experimental</td>
<td>Three tests conducted:</td>
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<td></td>
<td></td>
<td></td>
<td>152 MW&lt;sub&gt;el&lt;/sub&gt; coal fired power plant; 2000 t whole-crop Triticale, 1995 (Studstrup plant, normally fuelled with straw/coal mixture)</td>
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<tr>
<td></td>
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<td></td>
<td></td>
<td>CHP plant (Greenaa plant) with CFB boiler</td>
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<td></td>
<td></td>
<td></td>
<td>2.5 MW&lt;sub&gt;el&lt;/sub&gt;/7.7 MW&lt;sub&gt;th&lt;/sub&gt; CHP plant (Rudöping plant; 200 t combusted)</td>
</tr>
</tbody>
</table>

Abbreviations: CHP, combined heat and power; DH, district heating; EC, European Commission; FB, fluidized bed; IGCC, integrated gasification combined cycle; NFFO, non-fossil fuel obligation (U.K.); RCG, reed canary grass; SRC, short rotation coppice; THERMIE, EC programme for demonstration actions in the field of non-nuclear energy (1994–1998).
draw clear and final conclusions. In many countries there is a need for more demonstration plots and utilization projects, to allow for advances in machinery development and storage techniques. These should be monitored to fill the gaps in knowledge highlighted here.

4. UTILIZATION

4.1. Introduction

There has been very limited experience in the use of energy crops in Greece, Spain and Portugal. The most advanced countries in the use of solid biofuels based on energy crops are Sweden and Denmark, which is mainly a result of the heavy taxation of fossil fuels. The most advanced countries in terms of liquid biofuels (mainly biodiesel) are France, Germany and Austria. France is also advancing with bioethanol from sugar beet. The use of liquid biofuels is strongly stimulated by tax exemptions. An overview of selected major projects and plants aimed at use of energy crops for power and/or heat application in Europe is presented in Table 4.

4.2. Woody crops

4.2.1. SRC (willow and poplar)

4.2.2. Willow

Achievements. In Sweden, willow chips are commercially co-combusted in both small and large-scale power and heat plants. Two specific examples are a 4 MWth district heating plant near Lidköping and a CFB-power and heating plant in Örbero. The latter has a maximum capacity of 50 MWel/110 MWth and a nearby willow plantation of 2000 ha. Several thousands tonnes of willow are co-combusted annually with other fuels, which are coal, peat and forestry fuels.

Approximately 100 t of willow chips was combusted at a 5 MWth district heating plant in Denmark during a test in the winter of 1995/1996. The plant is normally fired with wood chips from forests. A similar test was carried out at a 3.6 MWth district heating plant during 1995. Preliminary surveys show that willow is one of the most suitable woody crops for combustion at district heating plants. However, some problems occurred due to the high moisture content (50–55%) of the willow used and the slightly higher content of Ca, K and P, resulting in more fouling and ash melting problems compared with forest chips. One way to solve the problem would be to co-combust willow chips with forestry wood chips, following the Swedish example.

A pilot 100 kWel/200 kWth CHP gasification unit uses SRC willow chips from nearby test fields in Northern Ireland. The system in operation in Enniskillen is currently being commercialized and will be ready for installation in 1997. Some of the problems which were identified during the running of the plant will be addressed during the development of the prototype by a commercial company. These include flow of the chips in the gasifier and the producer gas quality.

Some small-scale combustion projects for on farm heating purposes using SRC (willow and poplar) exist in the U.K., while under the Non Fossil Fuel Obligation 3 (NFFO), three medium-scale demonstration power plants using gasification technology for power generation have been granted licenses. One of these has also been given a THERMIE grant. The latter uses combined cycle technology linked to a fluidized bed gasifier and will generate 8 MWel. The other two will both generate 5 MWel by means of gas engines.

In addition, in Italy, a demonstration project aimed at the gasification of SRC together with other agricultural and/or forestry residual biomass is planned. The 12 MWel plant will generate power by an integrated combined cycle coupled to the gasifier (IGCC). The plant should be built near Pisa within the framework of the THERMIE programme by the Italian National Board for Electric Power (ENEL).

Laboratory-scale drop-tube tests and numerical modelling have been used in the Netherlands to examine how SRC and other energy crops would behave in a pulverized coal fired power plant. In addition, gasification tests have been conducted to characterize the behaviour of willow in a down-draft gasifier. Willow is considered seriously by some electricity power companies as one of the energy crops suitable for electricity generation on a large-scale.

4.2.3. Analysis. As with other biomass species, volatile inorganic compounds like K and Cl in willow may cause fouling and corrosion problems in combustion systems. In Sweden, specific problems with combustion of willow were solved by using fuel mixtures of both biomass and fossil fuels, thereby optimizing the combustion performance. Further in-
vestigations and full-scale tests with willow in different types of heating and power plants are necessary. One of the problems involved with combustion of biomass can be the disposal or use of ash. Further investigations into this subject are recommended.

There have been problems with the tar content in the producer gas of the Enniskillen gasifier in Northern Ireland. This is a characteristic of this technology at the present stage of development. It is also well known that fuel requirements are strict for fixed bed gasifiers. Further research and development on fuel quality and tar removal remains necessary to develop small-scale gasifiers suitable for full commercial operation.

It is clear that with the tax structure favouring biomass in Sweden and Denmark, willow use is most advanced in these countries. For countries like the U.K. and the Netherlands, the economics have to be determined by either specific feasibility studies (Netherlands) or by operational experience with the planned gasification plants in the U.K.. However, for the Netherlands it is expected that even with the "Regulating Electricity Tax" of 1.4 ECU/kWh the financial balances will not be positive without some additional form of financial support.

4.2.4. Poplar

Achievements. Poplar SRC is less commercially developed than willow SRC. In Belgium, a small-scale down-draft gasifier pilot project using poplar SRC as fuel was launched by the Walloon region and Electrable, which is the country's largest electric power production company. The gasifier will use locally produced SRC and generate power by an internal combustion engine with a rated output of 150 kW. Like the gasification project in Enniskillen, Northern Ireland, the whole bioenergy chain from SRC production to the sale of power to the grid is considered.

In Germany, briquette production and combustion of poplar have been studied and tested. Although the briquettes can be used in small-scale firing systems, there is no market for these briquettes in Germany presently. Several studies on poplar combustion have been carried out for applications on the household level and small-scale heating plants up to 3 MW, but have not resulted in commercial applications. It was calculated that for a 1 MW heating plant, the electricity costs with poplar were 30% higher than with heating oil.

Poplar is gasified both on laboratory-scale and pilot-scale for power production in Finland. Flash pyrolysis of woody material, resulting in pyrolysis oil, is also considered at a fundamental R&D level. Three new laboratory and PDU-units are installed by VTT now, while several companies are testing the suitability of pyrolysis oil for use in existing machinery. In Finland, pyrolysis oil for heat and power production in stationary diesel engines is considered economically attractive.

4.2.5. Analysis. In Belgium, Denmark, Sweden and Germany, the high moisture content of poplar coppice (50–60% at harvest), resulting in low calorific values, is considered a major disadvantage. Solutions are either drying or co-combustion with dried or fossil fuels. According to the Finnish country report, the main advantage of flash pyrolysis is the lower costs compared with vegetable oils; in particular, turnip rape seed oil.

4.3. Herbaceous energy crops

4.3.1. Miscanthus

4.3.2. Achievements. In Denmark, Miscanthus co-firing combustion tests were carried out in the commercial 150 MW straw/coal fired Studstrup power plant. In total 150 tonne of Miscanthus were co-combusted over 10 h. The percentage of co-combusted Miscanthus was, respectively, 15 and 30% on a weight basis. Although the results were encouraging, long-term co-combustion trials are needed to obtain more performance data for daily operation. At the level of district heating stations and CHP plants, preliminary studies and tests in Denmark indicate that Miscanthus and willow are more suitable for combustion than energy grain and straw. Some Miscanthus species (not Miscanthus 'Giganteus') are reported to have a lower content of Cl and K than straw from grain, thereby reducing corrosion and fouling of the boiler. A disadvantage is that due to the high potassium content the flue ash cannot be used in the cement industry. Reduction of the potassium content is therefore necessary to generate income from this by-product.

For Austria, it is believed that the existing straw fired heating plants are also suitable for Miscanthus bales. It was stated that the energy density and the flow properties of chopped Miscanthus are better than of chopped straw. In a small demonstration project, chopped Miscanthus was used for residential heating in
a 40 kWth farm boiler. No major problems were reported, although some remarks were made emphasizing the importance of a good fuel quality (moisture content, low ash content). In Denmark, tests have shown that big baled Miscanthus is suitable for combustion in farm heating plants designed for straw combustion. In particular, batch stokers are very suitable.

In Germany, gasification and combustion of Miscanthus have been examined since the late 1980s. Experiments have been carried out with an experimental 500 kWth unit originally designed for pulverized coal combustion. It was stated the amount of volatiles in Miscanthus is nearly three times as high as in coal, which implies that the ignition stability of Miscanthus flames is much better. The burn out may even increase due to the better ignition stability and higher reactivity. Since Miscanthus has a low melting point, care needs to be taken to avoid too high temperatures in the combustion chamber, which results in slagging. It was also concluded that due to the low melting point there is a technical limit to the share of Miscanthus that can be co-combusted with other fuels like hard coal. Just recently, a study on Miscanthus for power production for the large German power producer "PreusenElektra" was completed.

4.3.3. Analysis. The only large-scale co-combustion tests with Miscanthus have been carried out in Denmark in a fluidized bed boiler for power generation. To determine the feasibility of co-combustion or gasification of Miscanthus on a large-scale, further long-term tests are recommended. This may require collection of grown Miscanthus from several sites to get the amounts needed for reliable, long-term runs.

4.3.4. Reed canary grass (RCG/Phalaris)

4.3.5. Achievements. In Sweden, willow and RCG are considered as the two most promising energy crops. RCG has been tested in a research project as fuel for a 30 MWth powder burner producing heat. In a demonstration project, a 2 MWth heating plant, normally fuelled by dry wood chips from sawmills, is supplied by RCG from a nearby 200 ha plantation. The 2 MWth district heating plant is owned and operated by three farmers. The best results were obtained with mixtures of RCG and waste wood chips. A 9 h test in the 30 MWth heating plant showed higher NOx emissions and some fouling. The test was too short to optimize the combustion conditions which would result in lower NOx emissions. Concerning the ash, it is expected that conventional soot blowing techniques can be used to reduce fouling of the boiler. Extensive fuel analyses show that a delayed harvest decreases the ash and chlorine content, while the ash melting point increases considerably and the moisture content is low. These are significant advances for most thermal conversion processes. Plants grown on heavy clay soils give the highest ash content, those on humus rich soils the lowest.

In Finland, RCG (P. arundinacea L.) is considered the most interesting and promising energy crop. The grass can be used without any pre-treatment in mixtures of wood chips, peat and coal. Conversion techniques, tested on different scales ranging from laboratory to full scale, include flash pyrolysis, gasification and (co-) combustion. From laboratory tests it was concluded that co-combustion, especially with peat, is the best way to use herbaceous material like RCG for energy production. Another interesting option for Finland is to produce pulp. The reject fraction could be used for energy purposes; for example, by making pellets from a mixture of the waste and peat. These pellets were tested in a 300 kWth boiler that is normally fired with sod peat and occasionally with wood chips.

In the U.K., the dry matter content of RCG at harvest is considered an advantage. A disadvantage is the high ash content, but this can be tackled. There is no experience with the combustion of RCG in the U.K. yet.

4.3.6. Analysis. For Sweden, it is concluded that RCG (with the delayed harvesting method) is very dry, which means that the fuel is suitable for upgrading to briquettes, pellets and fuel powder. During combustion, the high ash (6% db) and silica content (as compared with wood chips) may cause fouling. Co-combustion with other fuels can solve this problem. Another route could be the development of boiler systems which are suited to handle
the high ash and silica content in RCG. In Finland, thermochemical conversion of RCG is considered as one of the most promising routes. However, as for other energy crops in Finland, even with decreased costs over the whole bioenergy chain in future, some fiscal or subsidy measures are necessary to make the use of RCG economically feasible.

4.3.7. Hemp. From an ecological and environmental point of view, hemp is considered as a promising crop in the Netherlands. However, no work on thermal conversion of hemp was reported. In Austria, it was reported that due to the fibre structure, hemp would be less suitable for chipping and baling and is hence not considered as a promising fuel. Flax shives, the by-product of the fibre production, could be more suitable for energy generation.

4.3.8. Energy grain (whole crop Triticale)

4.3.9. Achievements. In Denmark, three whole crop energy grain combustion tests at commercial plants were reported. The capacity of the first CHP plant is 2.5 MW_{el}/7.7 MW_{th} with a fuel throughput of 12 000 odt/yr. In total 200 t of energy grain was combusted. The second coal fired power plant had a capacity of 152 MW_{el} and is normally fuelled by a mixture of straw and coal. The third plant is a CHP plant with a CFB boiler.

Combustion of energy grain has been investigated in Austria, but is not common practice or commercialized. Potentially, the straw fired district heating plants, with a total capacity of 25 MW_{th}, would be suitable for combustion of energy grain. The present economic conditions are, however, not favourable.

4.4. Oilseed crops

4.4.1. Rape seed oil/RME

4.4.2. Introduction. Rape oil is obtained by extraction (pressing) of seed rape. The by-products are oil cake and glycerine, which are used as cattle feed and as feedstock for the chemical industry, respectively. After esterification with methanol, resulting in rape methyl ester (RME), it can be used as alternative for fossil based diesel oil in conventional diesel engines. Application of unprocessed rape oil is possible in specially developed biodiesel engines like the Elsbett engine. An overview of the achievements with respect to energy crops for transport fuels on a commercial scale in Europe is presented in Table 5.

4.4.3. Achievements. In France, five industrial esterification (pilot/experimental) plants with a total capacity of 240 000 t RME/yr are in operation, while an additional capacity of 190 000 t/yr is planned. A close collaboration between oil companies and the agricultural sector has resulted in an institutional structure for the production and supply of mostly blended diesel (5% biodiesel added). A higher mixing rate (over 30%) of biodiesel is promoted to overcome marketing barriers. One of the incentives for RME production at such a scale in France has been the 100% tax relief on pilot units and experimental projects for methyl esters (RME, SME) used as biofuels for engines or boilers. In addition, there is a uniform tax relief for esters added to diesel or domestic fuels. The upper limit for this tax exemption is 0.35 ECU/l or about 9 ECU/GJ.

In Germany, the use of rape as a source of bioenergy has been widely tested. In 1991 the first German experimental plant with a capacity of 1000 l/day was put into operation in Leer, north-west Germany. In 1995 a commercial plant with a capacity of 60 000 t/yr followed at the same site. Present transesterification capacity is 265 000 t in Germany (divided over four plants). Another three plants with an additional capacity of about 160 000 t/yr are planned. The positive results of previous experiments with RME in common diesel engines has resulted in widespread use of RME in Germany. For example, taxis in Freiburg and Berlin run on RME. All new VW diesel models are suited for the use of RME since August 1995. By this time 350 petrol stations were selling RME in Germany. Many projects, for example, the EU-project “Euro-Biodiesel” and also numerous smaller projects, are now on-going. In addition to the use of RME as transport fuel, RME is used in a few block heating systems.

Biodiesel based on rape or sunflower is produced commercially on an industrial and cooperatives scale in Austria. The first industrial biodiesel production plant (capacity 10 000 t/yr) in the world went into operation in Austria in 1991. Total capacity for rape and sunflower oil amounts to 35 000 tonne per annum, while 15 000 t of biodiesel based on rape was produced in 1995. By the end of 1995, the price of biodiesel was nearly the same as fossil diesel fuel. The tax exemption for pure biodiesel is about 95% (see Fig. 3).
Table 5. Overview of commercial production capacity for transport fuels based on energy crops in Europe

<table>
<thead>
<tr>
<th>Energy crop</th>
<th>Area cultivated for energy purposes in Europe (ha)</th>
<th>Countries in which energy crop is most developed</th>
<th>Status</th>
<th>Production capacity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rape seed + sunflower</td>
<td>800,000 + 391,000</td>
<td>France, Germany, Austria, Italy</td>
<td>Commercial</td>
<td>Installed capacity of 240,000 t RME/yr (five plants)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Planned additional capacity 190,000 t RME/yr</td>
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<td></td>
<td></td>
<td>Total future capacity 430,000 t RME/yr</td>
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<td></td>
<td>Present capacity 265,000 t/yr (four plants)</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>Planned additional capacity 160,000 t/yr</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Total future capacity 425,000 t/yr</td>
</tr>
<tr>
<td>Sugar beet</td>
<td>6250</td>
<td>France</td>
<td>Commercial</td>
<td>Installed capacity: 450,000 hl bioethanol/yr (ELF, one plant)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Planned additional capacity: 700,000 hl bioethanol/yr (TOTAL, two plants)</td>
</tr>
</tbody>
</table>

Abbreviations: RME, rape methyl ester; SME, sunflower methyl ester; hl, 100 l.

Instead of rape seed oil, sunflower oil can also be esterified, resulting in sunflower methyl ester (SME). With respect to SME, Austria reports that due to the high iodine number of sunflower oil, SME was not approved as diesel fuel by engine manufacturers as it may lead to carbon built-up in the engine and polymerization of the engine oil. Therefore, sunflowers with lower oil iodine number were developed. However, the higher content of saturated fatty acids and the wax content results in worse cold temperature flow properties as compared with RME and conventional diesel oil. It is therefore suggested by Austria to use SME as automotive fuel in the countries with mild climates in southern Europe.

Industrial production of biodiesel based on both rape and sunflower is also reported for Italy. The total installed capacity of 12 companies is more than $1.1 \times 10^4$ t of biodiesel per year. However, only 76,500 t of sunflower and rape oil methyl ester was produced during 1994/95. The enormous gap between the plants’ capacity and the actual biofuel production is due to: the high biodiesel production costs (2–3 times the costs of fossil fuels); the uncertain government policy, especially as it concerns tax relief (at present a quota of 125,000 t/yr is fully exempted from taxes).

In Ireland, two pilot projects on the use of biodiesel (RME) in commercial vehicles are reported. In the first project pure biodiesel was used in buses, trucks and a pleasure cruiser. The RME used was obtained through oil extraction followed by esterification on a small-scale tractor-mounted esterification unit. The second project involves a comparative analysis of the behaviour of a number of vehicles operated on RME and SME, imported from U.K. and Italy, respectively. Vehicle testing started mid 1996. A principal disadvantage of oilseed rape as a source of biodiesel in Ireland is its economic feasibility, as it is up to 0.25 ECU/l (about 6.6 ECU/GJ) more expensive than its fossil based equivalent.

In Denmark, two companies produce non-food rape seed oil, on a commercial basis, for export. At present, there is no commercial production of biodiesel in Denmark. During a test, four city buses were running on biodiesel during a period of three months. The results were promising, but not satisfactory from the environmental point of view. The Danish national transport plan “Trafik 2000” mentions the use of biofuels as one out of five major instruments to be used to reduce CO$_2$ emissions from the transport sector. However, there is no commitment for large scale use within the government.

In Finland, the costs for producing RME are too high to be competitive without major subsidies. The price is three to four times as high as for fossil diesel oil. The more feasible way on using rape oil is to mix it with conventional diesel oil and add only a little portion of RME. Unprocessed turnip rape seed oil has been tested in a 1.5 MW engine at VTT during 197 h. No results were reported.

In Belgium, a demonstration project on the use of biodiesel (RME) as automotive fuel was carried out. Both cars and buses were involved in the project. The rape seed was cultivated on set-aside lands. It is reported that one com-
mercial RME production plant is present, but this plant produces esters for industrial applications and data were not made available. In the U.K., rape seed oil is grown extensively and on a commercial basis, but there is only 200 l/yr converted to RME and used as fuel.

4.4.4. Analysis. In France, the production of RME has reached the current level due to 100% tax exemptions for (pilot/experimental) production facilities and significant tax exemptions per litre of biodiesel sold. In addition, the strong lobby of the oil companies and agricultural sector has favoured the use of biodiesel on the present scale.

In Austria, biodiesel from rape oil is commercialized. The main reason behind the commercial status is the significant tax exemptions for biodiesel. RME is produced in cooperative and industrial-scale plants. The main scientific and technical problems are solved. There are no special problems with the production and harvesting and processing of rape seeds. An interesting point is that biodiesel is produced from a mix from RME, SME and FME (used frying oil methyl ester) in Austria.

In Italy, due to a quota on the production level of biodiesel which is free of taxes and the high diesel production costs, only a low percentage of the installed biodiesel production capacity is used at present. It is expected that, with uncertainties due to the unclear agricultural policy and without guarantees on adequate financial incentives such as tax measures, the production of biodiesel based on rape and sunflower oil will be further reduced.

As in France and Austria, the use of RME in Germany is favoured by tax exemption. At present the production costs for RME (1.17–1.4 ECU/l RME) are higher than for fossil diesel oil (0.57 ECU/l).

All countries utilizing biofuels based on rape seed oil stated that liquid biofuels can only be made attractive with tax exemptions. Finland found another solution to reduce costs in new patented blending of raw rape oil, light fuel oil and RME. The main advantage is that the blend can be used in any diesel engines without modifications.

4.5. Sugar rich energy crops

4.5.1. Introduction. Fermentation is a biochemical process resulting in the production of bioethanol. The distinction between the fermentation processes of different feedstocks lies in the pre-processing steps. Sugar crops like sugar beet and sweet sorghum yield sugar in the easiest form, while starchy crops (like wheat, maize, potato) require treatment with amylase-enzymes or acids to produce sugars. Woody crops require an extensive treatment with acids or cellulase-enzymes to convert cellulose into sugars. The sugars are converted to ethanol in the fermentation process. By distillation processes the degree of ethanol purity is increased. The resulting bioethanol is used in mixes or almost pure as alternative for petrol. Bioethanol can be upgraded to ETBE (ethyl-tert-butyl-ether), which can be mixed with pet-
rol, or can be used in slightly modified diesel engines.

4.5.2. Sugar beet

4.5.3. Achievements. In France, there are 26 distillation units producing $40 \times 10^6$ l of multipurpose alcohol from sugar beet. Only one unit produces ETBE, which is an ELF plant with a capacity of $4.5 \times 10^6$ l ethanol/yr. The oil company TOTAL plans another two ETBE refineries with a total capacity of $7 \times 10^6$ l ethanol/yr. Although sugar beet crops are already concentrated in the north and east of France, it appears that optimization of the production would significantly reduce the production costs. Currently, the sugar beet sector is more efficient with respect to the production of bioethanol than the wheat sector. The costs of ethanol production from sugar beet is approximately $0.45$ ECU/l. Oil and motor companies are directly involved in the use of bioethanol through fuel characterization and engine development. The application of tax reliefs to products derived from raw materials cultivated on set-aside lands has been applied to sugar beet in France since January 1995. A 100% tax relief can be granted to pilot units and experimental projects.

In Denmark, some research is carried out on bioethanol production from energy crops. However, no pilot or demonstration units were reported. In the Netherlands, small tests with buses were carried out, while tests with pleasure boats are on-going.

Although in Italy, ETBE is produced on a large scale, no energy crops are used as feedstock so far. The reason is that it is of no commercial interest since the present industrial production of ETBE is based only on surplus alcohol produced by fermentation and distillation of wine or fruit surpluses.

4.5.4. Analysis. Like with biodiesel, bioethanol has achieved its current status in France due to 100% tax exemptions for pilot and experimental projects and tax exemptions on the product itself. The status in Denmark and the Netherlands is characterized as between the research and pilot phase.

4.5.5. Sweet sorghum

4.5.6. Achievements. Although there is some experience with production of sweet sorghum in Europe, the experience of its use is very limited. So far, only desk studies have been made, in Belgium. The ethanol production capacity considered was up to $3 \times 10^6$ l annually.

4.5.7. Analysis. The production of bioethanol based on sweet sorghum is not feasible in Belgium. Tax exemptions are necessary to stimulate the use of liquid biofuels (bioethanol and RME). However, the Belgian government does not intend to stimulate biofuels because there is no European agreement on tax exemptions for biofuels; Belgian public finances faces a deficit; politicians are not convinced by the arguments in favour of biofuels.

4.5.8. Winter wheat. In Germany, potatoes and cereals (in particular wheat and rye) are being fermented to produce ethanol. However, this ethanol is consumed as beverages or in the pharmaceutical and cosmetic industries. Currently no ethanol for use as fuel is being produced in Germany. Ethanol could be very competitive with petrol only under the condition that no taxes are imposed on biofuels used in pure form. In this case, the production costs (excluding costs for engine adaptation and distribution) are at the same level ($0.475-0.8$ ECU/l) as the petrol price charged to the consumer ($0.835$ ECU/l: petrol $0.25$ ECU/l + fuel tax $0.49$ ECU/l + VAT $0.095$ ECU/l). This would mean a tax exemption of $0.23-0.55$ ECU/l or $6-15$ ECU/GJ). However, there is no financial support for ethanol production from the German government at the state nor at the federal level.

4.6. Energy ratios

As is well known by most experts, the energy output/input ratios for the liquid transport fuel crops are in the range of 1–6, while for the solid fuel crops the ratio is in between 14–30. An overview of energy output/input ratio’s reported by the country partners is presented in Table 6. The ratios were derived from in-depth studies throughout Europe. The range presented is mainly a result of the definition of system boundaries and input values. However, the difference in output/input ratios between liquid and solid energy crops is clear.

4.7. Conclusions and recommendations for the use of energy crops

(1) Energy crops for power/heat purposes require fuel specifications which cannot be fully met yet. One of the reasons is the lack of awareness in the agricultural sector of the needs of the energy sector. The latter sector typically requires low Cl, low K, low N and low moisture content. More R&D is needed on the relationship between fuel requirements,
Table 6. Output/input ratios of energy crops reported by EECO-project partners

<table>
<thead>
<tr>
<th>Crop</th>
<th>Country</th>
<th>Output/input ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solid biofuels</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SRC</td>
<td>U.K.</td>
<td>29</td>
</tr>
<tr>
<td>GE (poplar)</td>
<td>IR</td>
<td>19-30</td>
</tr>
<tr>
<td>SW (willow chips)</td>
<td>AU</td>
<td>14</td>
</tr>
<tr>
<td>DK (willow)</td>
<td></td>
<td>8</td>
</tr>
<tr>
<td>Miscanthus</td>
<td>GE</td>
<td>15-20</td>
</tr>
<tr>
<td>Reed Canary</td>
<td>DK</td>
<td>18</td>
</tr>
<tr>
<td>Grass</td>
<td>SW (bales)</td>
<td>14</td>
</tr>
<tr>
<td>Cereals</td>
<td>GE</td>
<td>8.5</td>
</tr>
<tr>
<td>Liquid transport fuels</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rape (biodiesel)</td>
<td>IR; RME excluding straw</td>
<td>2.5</td>
</tr>
<tr>
<td></td>
<td>IR; RME including straw</td>
<td>5.5</td>
</tr>
<tr>
<td></td>
<td>GE; RME excluding straw</td>
<td>5.5</td>
</tr>
<tr>
<td></td>
<td>BE; RME, three scenarios</td>
<td>1.1-4.5</td>
</tr>
<tr>
<td></td>
<td>AU; RME excluding straw</td>
<td>2.8</td>
</tr>
<tr>
<td></td>
<td>DK; including straw</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>FI; RME</td>
<td>2.1</td>
</tr>
<tr>
<td>Sunflower (biodiesel)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Winter wheat (bioethanol)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>GE; without residue and straw</td>
<td>1.1-1.7</td>
</tr>
<tr>
<td></td>
<td>GE; with residue, without straw</td>
<td>1.4-1.9</td>
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<tr>
<td></td>
<td>GE; with residue and straw</td>
<td>4.0-5.0</td>
</tr>
<tr>
<td></td>
<td>BE; three scenarios</td>
<td>1.1-5.9</td>
</tr>
<tr>
<td></td>
<td>FI</td>
<td>1.3</td>
</tr>
</tbody>
</table>

Selection of species and agricultural practices. In addition, the standardization of biofuel specifications and analysis methods is recommended.

(2) As indicated by Sweden and Denmark, an advantage of co-combustion is that it offers opportunities to compose optimal mixes of biofuels and fossil fuels, while only minor modifications to existing equipment are needed. It is therefore recommended to emphasize co-combustion of energy crops with other more commonly used fuels. Parallel to these co-combustion activities, small to medium-scale stand-alone plants for herbaceous energy crops could be developed. It is strongly recommended to use the experiences with straw fired power and/or heat plants for development of the latter.

(3) So far, only short-term co-combustion experiments with energy crops have been carried out. The duration of these experiments was not long enough to determine the optimized conditions for long-term operation. Larger and long-term scale tests on co-combustion of energy crops, especially for Miscanthus, poplar, willow and RCG, in fossil fuelled power plants are recommended to evaluate and improve long-term operation. This will require cross border cooperation in order to collect a sufficient amount of energy crops for those long-term tests.

(4) The technical barriers and institutional barriers for liquid biofuels are much smaller than for solid biofuels, while on the other hand, the energy output/input ratio's for solid biofuels are much higher than for liquid biofuels. For the present, a parallel development of the liquid biofuels and the solid biofuels for energy routes is recommended. In the long term, more room should be created for solid biofuels due the higher benefits for the environment as compared with these liquid biofuels.

(5) It is clear from this synthesis that both liquid and solid biofuels can be made economically feasible only with financial incentives such as tax exemptions (sufficient for liquid biofuels), heavier energy/environmental taxes on fossil fuels (like in Denmark and Sweden) and grants for the farmers who cultivate energy crops grown on set-aside land (like in the U.K.). If the current level of tax exemptions in France (maximum level 9 ECU/GJ) and Austria (7 ECU/GJ) would be generally allocated for solid biofuels throughout Europe, the potential for solid biofuels would be considerably improved. For such measures, political will is essential. Monetizing the environmental benefits could be one of the instruments to create more potential for energy crops.

(6) In southern European countries high yields are reported for the energy crops, but experience with use is lacking. It is recommended to stimulate energy crops use projects in this region as well.

(7) An advantage of the use of RME or SME is that the oil is biologically degradable. It is therefore suggested to consider making the use of RME/SME compulsory in environmentally sensitive areas. Examples are the forest sector (wood cutting), pleasure boats on lakes and holiday resorts. By starting the parallel implementation of RME/SME in such niche markets, biodiesel would create a viable and long-term market without any subsidies if it is the only fuel which is allowed.
5. OVERALL CONCLUSIONS AND RECOMMENDATIONS

(1) It is clear from the European Energy Crops Overview (EECO) Project that both liquid and solid biofuels can be made economically feasible only with financial incentives, like tax exemptions (as in France and Austria for liquid biofuels), heavier taxes on fossil fuels (like in Denmark and Sweden in the order of magnitude of 5-6 ECU/GJ for non-industrial users) and grants for the farmers who cultivate energy crops grown on set-aside land, fiscal measures.

(2) If the current level of tax exemptions in France (maximum level 9 ECU/GJ (0.35 ECU/l) for biodiesel and 13 ECU/GJ (0.50 ECU/l) for bioethanol) and Austria (7 ECU/GJ or 0.28 ECU/l for biodiesel) would be generally allocated for solid biofuels throughout Europe, most energy crops around Europe would be feasible. However, political will is essential. Monetizing of the environmental benefits could be just one of the instruments to create more potential for energy crops.

(3) The technical barriers and institutional barriers for liquid biofuels are much smaller than for solid biofuels since the first are traditional and well-known crops. On the other hand, the energy output/input ratios (as just one example of a set of environmental parameters) for solid biofuels (14-30) are much higher than for liquid biofuels (1-6). For the present, a parallel development of the liquid biofuels and the solid biofuels for energy routes is recommended. However, from the environmental point of view, in the long-term emphasis should be created on solid biofuels because of the higher benefits for the environment as compared with the liquid biofuels.

5.1. Production

(4) A large number of crops have been investigated for their potential use as energy crops in Europe. However, only a few have reached beyond the level of R&D and have become commercialized and grown on larger areas. These examples exists due to the political and financial support given by some countries and they have provided valuable information on the future demands for the implementation of energy crops in European agriculture.

(5) There is significant room for reduction of the specific production costs by development to higher yields at lower costs. The results with willow in Sweden are illustrative: by combining programmes on fundamental biological and environmental R&D and more applied programmes, high yielding clones with good tolerance to frost, pest and rust have been developed. The technical development led to a reduction of the plantation costs by 50% from 1200 to 600 ECU/ha in only 5 yr.

(6) In most production, cost calculations land rental and profit for the farmer are not included since land rental is currently more or less covered by the set-aside regulation. However, this may not be the case in the future. This uncertainty is especially a barrier to the production of perennial energy crops. Therefore, there is a need for a long-term stability with regard to the status of energy crops in the Common Agricultural Policy. In addition, standard economic calculations including all costs and a realistic income for the farmer are recommended. Grants, subsidies and fiscal measures should be subtracted afterwards.

(7) The major bottlenecks and gaps of knowledge to be focused on in further R&D on energy crop production are: breeding in order to develop better adapted plant material with low input production and maximized fuel quality; low cost establishment of perennial crops; efficient and environmentally sound weed treatment; energy crops' water needs and its implications for productivity and ground water recharge; possibilities for use of wastewater, sludge and/or ashes in energy crops; the influence of factors such as genotype, harvest time, fertilization and climate on crop quality for energy purposes; and finally, effective dissemination of knowledge on new crops to farmers since this is a key issue for the successful introduction of new crops in agriculture.

(8) There is a need for further integration of agricultural practices and the energy sector. Energy crops for power and heat purposes require fuel specifications which are not fully met yet. One of the reasons is the unawareness in the agricultural sector of the needs of the energy sector.

5.2. Harvesting and processing

(9) There are barriers of agricultural acceptance for new energy crops which must be overcome and new technology such as harvesters and balers must be developed. Some
energy crops do not have the same problems because they are currently grown for non-energy purposes and can be cultivated and harvested by existing machinery. To reduce these barriers and the associated high costs, it is recommended to stimulate the development of effective low cost machinery for harvesting and processing energy crops in close cooperation with potential manufacturers and suppliers.

(10) Where the development of energy crops is in the demonstration and commercial phases (Scandinavia, Austria etc.), a lot of information is available. Many of the systems described are up and running. In other countries, information about transport, storage and economics is more limited. In these cases, the information is speculative, taken from models, resource studies and “educated” assumptions. One of the reasons for this is that in particular the logistics and associated costs are very site and case-specific. This makes it very difficult to draw clear and final conclusions from the total spectrum of data submitted. In many countries there is a need for more demonstration pilots and use projects, to allow for advances in machinery development and advances in storage techniques.

5.3. Utilization

(11) It is clear that the most advanced energy crops for heat and power generation, in commercial terms are short rotation willow and poplar coppice. In Sweden, and Denmark it is being grown and utilized commercially in rural heating systems and CHP plants. These facilities are also able to utilize energy grasses such as Miscanthus and RCG and in Finland, Sweden and Denmark large demonstration plots are being used for energy purposes. Co-combustion with other biomass or fossil fuels may be the future role for many energy crops.

(12) So far, only short-term co-combustion experiments with energy crops have been carried out. The duration of these experiments was not long enough to determine the optimized conditions for long-term operation. Larger and long-term scale tests on co-combustion of energy crops (especially for Miscanthus, poplar, willow, RCG and hemp) in fossil fuelled power plants are recommended to evaluate and improve long-term operation. This will require cross border cooperation in order to collect a sufficient amount of energy crops for the long-term tests.

(13) Parallel to these co-combustion activities, small- to medium-scale stand-alone plants for herbaceous energy crops could be developed, based on the experiences with straw fired power and/or heat plants.

5.4. Dissemination and exchange of information

(14) The EECO project has yielded a wealth of information on energy crops, of which only a selection is presented in this synthesis report. To maximize the use of the valuable information presently available, it is recommended to develop and utilize instruments which further increases the exchange and dissemination of the information on energy crops yielded by this EECO project and by other networks in which the EECO partners participate. One of the instruments could be Internet, as proposed by the EECO-project partners in the European Energy Crops Information Exchange and Dissemination InterNetwork (EECI Network).

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