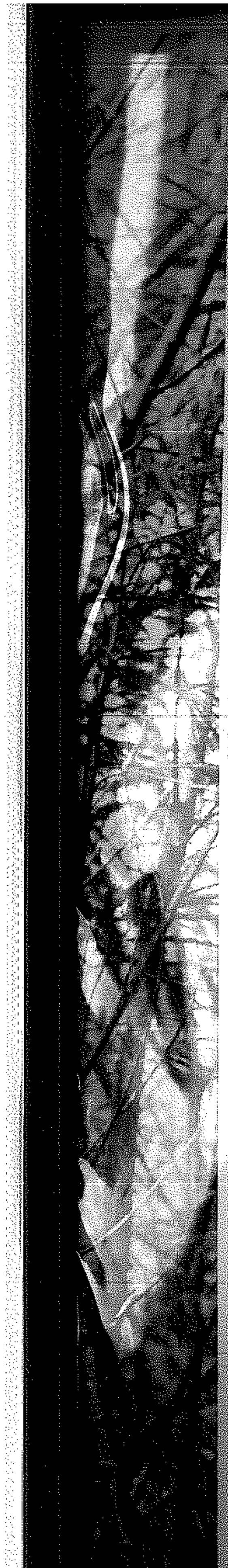

RECOVER

Relevancy of Short Rotation Coppice Vegetation for the Remediation of Contaminated Areas

Final Report

1999

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CENTRE D'ETUDE DE L'ENERGIE NUCLEAIRE

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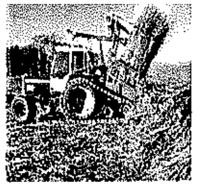

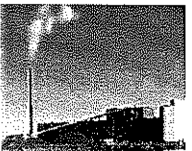

Summary

When dealing with large-scale environmental (radioactive) contamination, a sound and sustainable remediation strategy should be advocated. Such a remediation strategy should not consist of one simple option but of a combination of measures adapted to the site-specific conditions. Change in land use as a countermeasure is the modification of existing agricultural practice such that the products from the land are radiologically acceptable. Impact on dose to people and on the ecology and economy of the affected area may vary enormously: for, example change in crop variety will have much smaller impact than more radical changes as the substitution of vegetables by cereals or changing from an arable or cattle system to forestry. Some changes will necessarily be in place for many years and though radiological benefits may continue, ecological, economic and social consequences may accrue during this period. Therefore, before advocating and implementing substantial changes in land use, the situation and the possible consequences of the remediation strategies should be thoroughly assessed.

For agricultural land, one possible measure is to use the land for non-food production. The use of vegetable products (biomass) for energy, instead of fossil fuels, may be a valuable land use option for severely contaminated areas where food crop production is banned or restricted on radiological grounds.

The emphasis in present study is on the evaluation of *Short Rotation Coppice (SRC)* for energy purposes as a bioalternative for remediation of contaminated waste farm land with restricted uses. Other potential energy crops (rape seed, winter wheat and sugar beet) are also discussed but in lesser detail. The cultivation of energy crops in contaminated areas may have both positive and negative effects on radiological grounds. Studies on the radiological and radioecological consequences of the implementation of alternative crops are, however, scarce. Moreover, general ecological, economical and social aspects should also be considered before advocating energy crops as a suitable corrective action.

Two different regions were studied: importance is dedicated to Belarus, of which a large part of the territory was severely contaminated as a result of the accident in the Chernobyl nuclear power plant, and Western Europe, where energy crops have already been studied rather intensively, except for radiological issues.

The principal questions we have answered are:

- What is the fate of radiocaesium in a willow cultivation system and other bio-fuel routes and what is the expected radiocaesium concentration in the end-products?
- How does radiocaesium behave during the biomass processing?
- What is the dose acquired during biomass cultivation and processing?
- How well are the crops adapted to the climate and soil conditions in Western Europe and Belarus?
- How ecological sustainable is the cultivation of willow short rotation coppice and the other energy crops in terms of energy efficiency, CO_2 release, nutrient leaching and waste generation?
- What are the conclusions with regard to economic feasibility for the production and use of these energy crops in Western Europe and Belarus?
- What are the perspectives for these various energy crops, with emphasis on SRC, as alternative landuse for large contaminated surfaces?

General aspects: cultures, conversion routes and regions considered.
In the SRC concept, fast growing tree species like willow (*Salix spp.*) are intensively managed and harvested for biomass (stems) in three to five year cutting cycles for a 22 to 25 years crop lifetime. The harvested biomass is converted into heat or electricity. The cultivation is not labour intensive and specialised agricultural equipment is preferred but not necessarily needed. As conversion techniques, small-to-large-scale combustion and gasification units producing heat and/or electricity are considered. Small-scale plants are possibly very interesting for decentralised power production.

Three other potential energy crops are studied in less detail: oil seed rape (OSR), winter wheat (WW) and sugar beet (SB). The conversion routes considered are for OSR esterification to produce rape methyl esters and for WW and SB fermentation to produce ethanol. These crops were selected since they are already

grown in Belarus and their biofuel conversion routes are well known in Western Europe. Technical and economic feasibility is discussed for Western European and Belarus conditions.

Radiocaesium levels in end products of production and conversion
Flux of radionuclides should be studied to obtain information on the radionuclide levels in the wood (exploitable plant part) and in the ashes after combustion. Emphasis is on radiocaesium, the major radionuclide in the environment contaminated by the Chernobyl fall-out. Radiocaesium behaviour is studied in a coppice ecosystem by investigating the soil-to-plant transfer on lysimeter scale (detailed study), on farmer's sites in Sweden and on test sites in Belarus. Further the radiocaesium flux during conversion is discussed.

On radio-ecological grounds there is not too much concern for none of the cultures. Activity levels in the useable plant parts are generally low and the same holds for the waste products.

Estimates for the radiocaesium concentration in the willow wood can only be given with a substantial uncertainty (as is for most crops). We were unable to derive transfer factor functions for estimating the radiocaesium content in willow wood from soil characteristics. For specific soil groups an exponential relationship between the TF and the soil solution potassium concentration was found, but parameter estimates were different for different groups and reasons behind could not be revealed based on the vast number of soil parameters determined.

Broadly we can say that in light textured soils with a low radiocaesium interception potential (RIP) the TF to wood varies between 0.5 10^{-3} and 2 10^{-3} m^2 kg^{-1} and, for soils with a medium to high RIP, between 0.2 10^{-3} and 5 10^{-5} m^2 kg^{-1}.

No effect of clone and stand maturity on TF could be derived. In the Swedish coppice trials only two coppice varieties were planted and crop age at the different sites was not always the same for both varieties. The variation in TF at the Belarus coppice trials was so high that no statistical difference in TF between the different coppice clones was found. For the effect of stand maturity on the TF, we could assume from the Belgian lysimeter trials that the radiocaesium TF would stabilise or even decrease from the second growing season after cutback onwards.

The radiocaesium which accumulates in the willow roots was shown to become constant from the second year of cultivation onwards. It may be expected that all caesium incorporated will be highly available at the time of grubbing up (end of a coppice cultivation cycle), yet, less than 0.01 % of the soil radiocaesium is incorporated in the roots. Moreover, the caesium potentially released during root decomposition will for most soils be immediately fixed by the mineral fraction.

Comparison between the willows grown on the Belgian test sites and a 17 year-old-forest in Belarus (4 years-old at the time of the accident) has shown that the net annual radiocaesium accumulation is about 35 times higher in the forest standing biomass than in coppice. Moreover, annual biomass increase is only 6 t ha^{-1} for forests and may attain 12 t ha^{-1} for SRC grown on soils with an adequate water reserve and fertility status. On these types of soil, SRC may hence be a more promising land-use option than traditional forestry. On soils with low water reserve (e.g. sandy soil) willow yield without irrigation is maximally about 5 t ha^{-1}, and here forestry may be the preferred option.

If the TF to SRC wood applies for coppice grown on relatively fertile soil with a moderate to high RIP, wood can be safely burnt and the ashes can be disposed off without concern. In case the high SRC-TFs for low-RIP soils pertain (2 10^{-3} m^2 kg^{-1}), which is potentially relevant for low fertile and low RIP soils, possibly acid and with a high ammonium concentration in the soil solution, wood burning would only be permitted when willow is grown on a soil contaminated with <370 kBq m^{-2} ^{137}Cs (considering Belarus exemption limit for fuelwood of 740 Bq kg^{-1}). Given that TFs for common forestry (2 10^{-3} m^2 kg^{-1}) and for straw of winter wheat and oil seed rape (0.3 10^{-3} and 0.63 10^{-3} m^2 kg^{-1}) are comparable, the same applies for burning wood or straw for energy. At higher soil contamination levels, wood (straw) could potentially still be burnt in commercial electricity or heat plants but adequate exhaust filtering systems should be installed and appropriate disposal of the ashes should follow. In Belarus, waste and contaminated biomass from the Chernobyl accident can be incinerated if activity levels do not exceed 3.7 MBq kg^{-1}.

Different combustion techniques and type of power plants exist which affects the enrichment of radiocaesium in the ashes. Broadly, caesium-enrichment factors (Bq kg^{-1} ash / Bq kg^{-1} wood) for the ashes vary between 20 and 100. Fractions of caesium escaping through the stack vary between 1 % (modern filtering systems) to an upper 12 %.

TF to the useable products (rape seed, wheat grains, beet root) for the other biofuel crops considered range between 0.08 and 0.5 10^{-3} m^2 kg^{-1} and the liquid biofuels are almost free from activity. No information was found on the TF of radiocaesium to the by-products of the liquid biofuel cycles. Also radiocaesium levels in the waste-products are generally of no concern. In case of high deposition (~ 1000 kBq m^{-2}), Cs-levels in the oil cake from OSR (~2000 t ha^{-1}) and the pulp and vines from SB (~ 4000 t ha^{-1}) exceed the exemption level for use as animal fodder and for incineration and should, therefore, be disposed off. Since amounts to be disposed off are substantial, this involves a high disposal cost (up to 20 and 60 % of the revenue for OSR and SB, respectively). Possibly this waste could also be burnt in order to reduce its volume by about 90 %.

Radiation exposure
In case of high contamination levels in the wood (3000 Bq kg^{-1}) (or straw or oil cake and pulp) doses at different locations in the power plant may exceed the acceptable level of 1 mSv a^{-1} for a member of the general public. The highest doses are at the fly-ash silo (16.4 and 3.5 mSv a^{-1} if 2000h at a distance of 0.5 or 5 m, respectively, from the collector). Under such conditions, workers should best be controlled (personal dosimeters). With appropriate work-rotation-schemes doses can most probably be brought down to less than 1 mSv a^{-1}, even in case of high(er) contamination levels. Doses in the close vicinity of an ash deposit of mentioned highly contaminated ash might as well exceed the dose limit for the general public. Therefore, also people dealing with the ash handling and working at the ash disposal site should be controlled. Contributions from other possible radiation pathways are negligible (external exposure during culturing and transport, inhalation dose in the plant and to the general public following wood or liquid bio-fuel burning).

Crop requirements and yield
The potential yield of all four crops studied is about 10 % lower under the continental Belarus climate compared to yield estimates in Western Europe on a soil without water and nutrient limitations. Since the precipitation is mainly concentrated in autumn-spring in Belarus, potential-yield estimates on a sandy soil (low water holding capacity) are only 50 % for SRC and SB and only about 30 % for WW and OSR than yield for a soil with an adequate water reserve. Since yield is an important parameter controlling economic viability, appropriate yield levels are important.
Compared to the other biofuel crops considered, SRC is little demanding in terms of pesticides and fertilisation. As an example, from the lysimeter study (and confirmed by literature data) it was shown that already from the second year onwards, the SRC system is practically autosufficient with regard to potassium, due to retranslocation in autumn, recycling through litterfall and input by precipitation. Further, SRC can grow on a wide range of soils.

Ecological sustainability
Regarding the ecological sustainability of cultivating crops for energy production, the electricity or heat routes have much better energy and carbon budgets than the liquid fuel routes. For the wood fuel system, there are still considerable uncertainties in the estimates for the energy and carbon balance. However, when compared with gas and coal fired power plants, energy requirements are respectively a factor 16 and 23 lower. CO_2 emissions from wood fuel burning are a factor 11 and 25 lower than for gas and coal burning. The overall energy efficiency of the SRC-route ranges between 10 and 30. For the liquid bio-fuels, the energy efficiency is close to one. Reduction of CO_2 emissions when using bio-fuels as transport fuel is maximally about a factor 1.5 to 3, with by-products included 2.5 to 3.
Further, mineral and pesticide emissions are high for OSR, WW and SB cultivation and erosion risk may be pronounced (SB). For SRC, pesticide and fertiliser use is limited and leaching to water table is insignificant. We showed that nitrate levels in the leaching water under SRC was a factor 4 lower than under common annual cropping systems. Water requirements are comparable for all crops.

Economic profitability

The economic sustainability of cultivation and conversion of energy crops was evaluated for Western Europe and Belarus. Different scales/modes of production and conversion were studied. Important differences in system parameters between both regions are that labour costs are a factor of at least ten lower in Belarus, no grants are available in Belarus, farm machinery prices are lower in Belarus by up to a factor of five, domestic heat and electricity prices are much lower in Belarus and finally, boilers for heat production are cheaper by a factor of three to five in Belarus.

In Western Europe, electricity production from SRC is currently only viable with both production incentives and electricity price support at the conversion side.

The cost of production of SRC in Belarus is potentially lower than in Western Europe, due to the lower labour and machinery costs. However, to maintain this advantage, the yield of SRC in Belarus must approach that in Western Europe. A 50 % reduction in yield renders the system un-economic. This implies that SRC cultivation for energy production on sandy soils under the Belarus continental climate conditions will hardly be profitable since the potential yield is only about 5 t ha^{-1}. Sandy soils should therefore be irrigated and fertilised or used for more appropriate cultures (e.g. pine forest). The cost–effectiveness of this action was, however, not investigated. Since about 60 % of the soils in Belarus are of a sandy nature, only a small percentage of soils are apt for SRC cultivation. This may impinge on transport distance and availability of product, affecting both profitability of production (if transport costs are to be paid by the farmer) and conversion (availability). On the other hand, forests could be established on these marginal soils and since power plants can be fed by a variety of woody fuels, SRC and forestry may be very complementary land-uses.

An important parameter for system profitability is the bio-fuel price at delivery at the plant. To make production profitable, about 40 EUR t^{-1} is required. At this bio-fuel price, which is a factor 4 higher than the amount paid for waste wood as biofuel, a profit can be made both at the production and the conversion site. The harvesting technique also affects the profitability at the production side: harvesting in chips is preferred to harvesting in sticks and separate chipping. Transport distance only affects production profitability to a limited extent.

For conversion, the most significant parameter was the price that could be achieved for the heat or electricity. In Belarus the domestic tariffs (0.001 and 0.0032 EUR kWh^{-1}, respectively) are much lower than the industrial tariffs (0.026 and 0.034 EUR kWh^{-1}), and none of the schemes considered were economic for domestic heat or electricity production.

For industrial tariffs, the heat schemes considered were all economic, under condition that they are run at a higher availability (e.g. 80 %) than the quoted 16 %. Heat schemes already exist in Belarus using forest residues as fuel. Our work has shown that SRC could be used as the fuel paying 40 EUR odt^{-1} to the producer for the delivered chipped fuel. Even when the costs of the conversion system are increased by a factor 3-4 to the costs quoted for Belarus, these conversion routes may still be viable.

For electricity production in Belarus the results are more speculative, since no conversion plant currently exists. In our original calculations we assumed a lower capital cost of conversion plant in Belarus than in W. Europe, which led to large and small scale schemes being marginally profitable where industrial electricity tariffs were achieved and availability was high. If capital cost of the power plant would be 50 % - 100 % of that in Western Europe, electricity production is not economic in Belarus without price support for the electricity, or capital grants for plant construction.

Only a small percentage of the revenue from energy production is to be dedicated to the waste disposal in case of the wood bio-fuel pathway. This will not render the profitable systems uneconomic.

Regarding the economics for the other three crops, OSR, WW and SB can be grown successfully in Belarus if soil conditions are appropriate to attain potential yields. In Western Europe, OSR production is only profitable with price support. Both in Belarus and Western Europe, the cost of liquid bio-fuels is about 3 to 4 times the cost of fossil fuels and hence price subsidy is needed to compete with fossil fuels. It is therefore highly improbable that these crops can be advocated as potential alternative crops for a contamination scenario since the production-conversion schemes are, even in non-contamination conditions, un-profitable. A nuclear accident will certainly affect the market structure, but how this will potentially change the profitability of the bio-fuel cycles is beyond the scope of this project.

We may hence conclude that the energy production from SRC is a potentially ecologically and economically sustainable land-use option in situation of contamination or not, but that its feasibility depends on a number of factors.

Broadly, for none of the cultures studied there is a major radiological concern. In case of considerable contamination, plant owners should be allowed to burn biomass which is contaminated above the acceptable level for burning fuel-wood. This would mean that different exemption limits should be in place for domestic and industrial use. Efficient filtering systems should be in place, disposal should be adequate and conversion plant workers and waste disposal people should be controlled. On the other hand, if the conversion routes are found profitable, disposal costs generally only account for a few percent of the revenue.

The economic viability of the systems should be thoroughly calculated through for the prevailing conditions. For Belarus, profitability at the production side largely depends on crop yield and price of the delivered bio-fuel. For appropriate soil conditions, potential yields are high for all crops. However, most of the territory consists of sandy soil, for which yield estimates are too low to make production profitable (if no irrigation). On mentioned sandy soils, certainly when exempted for food production, traditional forestry is probably the preferable land-use option, and may be complementary to SRC. On the other hand larger scale heat conversion systems seem the most profitable and revenue may be considerable. For smaller scale units, e.g. for decentralised heat production, conditions should be optimal to attain the break-even point. Electricity routes are generally unprofitable, unless they are exploited at almost maximum availability and when plant building costs are the ones quoted for Belarus.

An important disadvantage of growing a perennial crop is the higher risk for the farmer in comparison with cultivation of an annual crop. The high costs of investments for perennial crops can hardly abide the lack of flexibility and the amount of uncertainty. After having invested in SRC, farmers can only change to other crops at high costs. Compared to normal forestry, revenues arise from the third year onwards in SRC and only after 20 (first thinning)-80 years for forests. Perennials can not be included in rotation-set-aside schemes and large-scale practical experience is limited.

When advocating or installing a new culture and the connected conversion route, an important aspect to consider is also the infrastructure needed and the availability of a market to sell the product (heat and electricity). The viability of the system will also depend on the macroeconomics [price evolution of fossil fuels, electricity and heat (as already partly investigated), transport costs, etc] and on socio-political perception. In case of a severe contamination, perception and boundary economic conditions will certainly be affected. The assessment of the impact of macroeconomics and socio-political aspects, though extremely important, is, however, outside the scope of this project.

In a contamination scenario, when food crop production is banned or when there are psychological constraints to cultivate food crops, the land can be turned into value by the cultivation of bio-energy crops, without a real radiological concern. Heat and electricity routes (e.g. SRC) are preferred to bio-fuel routes for which production and conversion grants are required. Government incentives, political willingness, availability of a market and social acceptance are, however, indispensable.

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1 Objectives

When searching for suitable and sustainable remediation options in case of environmental (radioactive) contamination, radiological, ecological, economic and social aspects should be considered in the optimisation approach. In this regard is *Short Rotation Coppice* (SRC) cultivation for energy purposes evaluated as an innovative bioalternative for remediation of contaminated agricultural land.

The objective of this project was the *radiological, technical, ecological and economic evaluation of short rotation coppice as a realistic alternative for the remediation of contaminated farmland.* For fulfilling the overall objective of this project, following domains were elaborated:

1. Study of flux of radiocaesium and its analogue K in a willow cultivation system on experimental plots, at farmers' scale (Sweden) and test sites in Belarus. Additionally, the fate of radiocaesium during biomass conversion was investigated.
2. Assessment of dose received by persons dealing with coppice cultivation and subsequent processing of the biomass.
3. Evaluation of technico-agricultural feasibility of SRC and comparison with other bio-energy crops for specific climate and soil conditions (W. Europe, Belarus).
4. Calculation of energy and carbon balances and assessment of economic feasibility for cultivation and conversion of a number of energy crops: SRC, oil seed rape, winter wheat and sugar beet. Assessments are performed for W. European and Belarus conditions.
5. Identification of parameters affecting system viability and sustainability and discussion of perspectives of energy crops as alternative landuse option of contaminated areas.

2 Background

Following the Chernobyl accident, many thousands of square kilometres have been severely contaminated in the CIS. The application of corrective actions in contaminated areas remains a key issue in large territories of Russia, Ukraine and Belarus. In Belarus, approximately 4.3 Mha, including farmland and forests, were contaminated to levels in excess of 37 kBq m^{-2} (1 Ci km^{-2}). The application of simple clean-up operations leading to a rapid return of such a large area to its normal state, is unrealistic and would, in addition, generate an enormous amount of radioactive waste. Consequently, an important part of the contaminated agricultural land may be left deserted for many years, despite its agricultural potential remaining intact.

When agricultural perspectives must be abandoned in such territories because of irremediably high activity levels in food products or because of economically and technically non-realistic corrective options, an increasing interest arises in developing more integrated and ecologically-based approaches. In this regard, industrial crops not used for food production, may be an alternative remediation option.

In SRC cultivation, fast growing willows (*Salix spp.*) are intensively managed and harvested for biomass in three to five year cutting cycles and a 22-25 year crop duration. Fast growing willow species are among the fastest and highest biomass producers when optimally provided with water and nutrients (Ledin, 1996). The harvested biomass is converted into heat and power. As such this non-food production agricultural-industrial crop is a potential candidate for the valorisation of contaminated land with restrictive use.

Interest in the cultivation of energy crops is not just linked with the re-valuation of contaminated territories. For example, Belarus is presently importing more than 90 % of its energy. About half of the energy produced (1716 Mte from a total of 4027 Mte) is obtained from combustion of peat and wood (Gopa, 1996). Nevertheless it is acknowledged that wood has not yet been seriously exploited as an energy source for boiler plants. In a study on the oil seed rape as bio-energy source (GOPA, 1996) it was mentioned that there is some potential for some small-scale power plants. In comparable situations, small-scale gasification units could apply (see further). At first glance, Belarus conditions appear favourable for introducing renewable energy sources.

Also in Western European there is an increasing interest in the use of biomass as source of energy, the reason being that biomass as energy source is expected to have positive effects such as the reduction of the emissions of green house gases, the valuation of marginal areas, the creation of new opportunities for the agricultural sector and the useful allocation of land withdrawn from common agriculture.

These aspects may not have a direct relevance to a contamination scenario but they contribute to a favourable context, a positive attitude and willingness for market development all important aspects for novel developments/land uses, certainly in a contamination situation, to be acceptable at a large scale.

3 Radioecological considerations when advocating energy crops as alternative landuse

When proposing non-food crops as potential alternative landuse for severely contaminated land, information should be collected and knowledge gained on the fluxes of radionuclides in the cultivation (and conversion) systems proposed. Since short rotation coppice (SRC) was not yet considered as a possible re-valuation option for radioactively contaminated land, the flux of radionuclides should be studied to obtain information on the radionuclide levels in the wood (exploitable plant part) and in the ashes after combustion. Emphasis will be on radiocaesium, the major radionuclide in the environment contaminated by the Chernobyl fall-out.

Radiocaesium behaviour is studied in detail in a willow coppice ecosystem by investigating the soil-to-plant transfer and radiocaesium cycling on experimental scale (detailed study). Farmers' coppice stands established in N. Sweden after the Chernobyl accident were sampled to have a broader basis of transfer factors for different soil types, coppice clones and age classes. Test sites in Belarus were established to screen for the radionuclide transfer and yield potential of four coppice varieties in circumstances of elevated contamination, continental climate and poor soil conditions. Further the radiocaesium flux during biomass conversion is discussed.

Comparison is made with the radiocaesium flux in a pine forest stand and with the expected radiocaesium uptake by 3 other bioenergy crops (oil seed rape, sugar beet and winter wheat) and its fate during processing.

3.1 Transfer and cycling of radiocaesium in a SRC culture at experimental scale

3.1.1 Objectives

A detailed study of radiocaesium cycling in the willow SRC system is imperative for evaluating the culture as an alternative for food production on contaminated land. A study of radiocaesium concentration in the different plant parts (and especially in wood) during the growing season and over the years enables further to compare willow SRC with traditional forestry or other alternative non-food crops. Because several authors mentioned some similarities between radiocaesium and potassium in plants (Collander, 1941; Bunzl and Kracke, 1987; Broadley and Willey, 1997), potassium is included in the study. If certain similarities were to be found in present study, an extension of radiocaesium behaviour to following cropping cycles could be made based on what is known from potassium.

Recycling of radiocaesium to the soil by litter fall and litter decomposition and by leaching of the foliage (throughfall) is evaluated. Retranslocation patterns for radiocaesium were calculated and compared to those of potassium. Efficiency of uptake is evaluated.

3.1.2 Materials and methods

The upper 30 cm of the original sandy soil of 8 experimental plots (2 * 2 m^2) were replaced with the upper soil layer of an orthic luvisol (loamy soil, 4 plots) or an orthic podzol (sandy soil, 4 remaining plots) (FAO, 1990). The soils were homogeneously contaminated with ^{134}Cs by mixing the upper 25 cm with a ^{134}CsCl solution (about 8 10^6 Bq m^{-2}). Final contamination levels were 24 ± 6 10^3 Bq kg^{-1} dry soil for the loamy soil and 30 ± 4 10^3 Bq kg^{-1} dry soil for the sandy soil (difference in bulk density accounts for difference in contamination levels on weight basis). Selected soil characteristics are summarised in Table 1. The CEC was determined according to Chhabra *et al.* (1975) and the pH measured in 1 N KCl (1:2.5). Carbon content was determined by loss through ignition. The radiocaesium sorption by the soils was measured as the radiocaesium interception potential (RIP), and the solid-liquid coefficient K_D, [Bq kg^{-1}/Bq L^{-1}] can be calculated as K_D = RIP/m_K, with m_K the concentration of potassium in the soil solution (*M*) (Wauters *et al.*, 1996). Exchangeable cations were determined in a 1 M NH_4Ac extract at pH 7. Soil solution was isolated by centrifugation of soil samples (about 50 g), previously equilibrated for 24 hours with distilled water at field capacity. Cations in both extracts were analysed by Atomic Absorption Spectrophotometry (AAS). Radiocaesium concentration in the soil and in the respective extracts were determined with a γ-counter (Canberra Minaxi, 5530 auto-γ).

Two weeks after soil contamination (May 1996), the plots were planted with willows (*Salix viminalis* L. Var. Orm) with a density equivalent to 52 500 plants ha^{-1}. This relatively high density allowed for destructive samplings at the end of each growing season. Plant densities during the second and the third growing season were equivalent to 42 500 and 35 000 plants ha^{-1}, respectively. All results of biomass production or mineralomass are recalculated to the final plant density. One or two rows of plants were planted around and between the plots as a buffer zone. Fertilisers were added only in the beginning of the second growing season (June 1997) at a rate of 80 kg N ha^{-1}, 15 kg P ha^{-1} and 40 kg K ha^{-1}. Pests and diseases were controlled year-round and additional irrigation was provided intermittently during summer. Plants were coppiced (cut-back to promote regrowth) at the end of the first growing season. At the end of each growing season (R_1S_1, R_2S_1 and R_3S_2 plants: R_xS_y: Root x years old; Stem y year old) 3 or 4 entire plants per plot were sampled (stems, roots and cuttings).
During autumn, the litter was collected on nets covering the entire surface of the plot (0.1 m above the soil). Additionally, stems and leaves of R_2S_1 and R_3S_2 plants (2 or 3 shoots per plot) were sampled in April, June, August and October. At all sampling occasions, standing biomass was estimated from length (R_2S_1 plants) or diameter (R_3S_2 plants) following a relation "weight=f (length or biomass)" established with the stems sampled.
All plant parts of sampled plants were separated and dry weight determined (105 °C). Plants were analysed for ^{134}Cs concentration (γ-counting) and K concentration (calcination for minimum 24 h at 500 °C followed by mineralisation with HCl, 38 %). All activities reported were corrected for radioactive decay with respect to the planting date. Radiocaesium Transfer Factors (TF) are calculated as follows:

$$TF = \frac{[Cs]_{plant}}{[Cs]_{soil}} \qquad \text{(Eq. 1)}$$

with radiocaesium concentrations ([Cs]) in Bq kg^{-1} for plants and Bq m^{-2} for soil, unless indicated differently.

A litter decomposition test was carried out with the litter fallen in autumn 1997. Six litter bags per plot of the sandy soil, containing approximately 9 g of air dried litter, were placed on non-contaminated sandy soil. Mesh sizes were 1 mm at the bottom and 3 mm at the upper side. At each sampling occasion (after 1, 3, 7, 15, 23 and 31 weeks) one litter bag derived from each sandy soil experimental plot was analysed for dry biomass, radiocaesium and potassium concentration.
Leaching of elements from the foliage was studied from August 1997 until December 1998. Rainwater below the plant canopy was continuously collected with two gutters per plot and analysed for ^{134}Cs (concentrated on an exchange resin) and K concentration (AAS). A control gutter was placed outside the experimental plots to determine the input of potassium in the system by rainwater or dry deposition.

3.1.3 Results

3.1.3.1 Soil characteristics

The two soil types are characterised by a clearly different texture (Table 1). The higher RIP value for the latter soil type is likely a consequence of its finer texture. The sandy soil has a higher carbon content. The evolution over the years for exchangeable potassium and potassium concentration in the soil solution is given in Figure 1. Especially for the sandy soil, the exchangeable potassium content remains more or less constant. The concentration in the soil solution, however, decreases each year during the growing season (from March to December) and increases again a little during winter. This evolution is also found for the loamy soil. The decrease in K concentration is the largest in the first growing season, when the biomass production started from (nearly) zero. Also in the beginning of the second growing season the above-ground biomass is zero and biomass production very high. However, the soils were fertilised in June and are not depleted. In the third growing season, the K recycled by foliar leaching and litter and root decomposition, is sufficient to sustain crop growth and the system is assumed to have become sustainable in terms of K.

Table 1: Selected soil characteristics of the orthic luvisol and the orthic podzol at the start of the experiment [data are means and standard deviations (in brackets) of the 4 replicate plots]

Soil characteristics		**Orthic Luvisol - Loamy soil**		**Orthic Podzol - Sandy soil**	
CEC ($cmol_c\ kg^{-1}$)		10.6	(0.7)	6.7	(0.9)
Texture (%)	100-50 µm	10. 7	(0.7)	90.6	(4.9)
	50-20 µm	40.6	(2.6)	5.8	(0.3)
	20-10 µm	31.7	(1.6)	0.6	(0.1)
	10-2 µm	2.0	(0.03)	0.7	(0.3)
	< 2 µm	15.0	(0.3)	2.3	(0.5)
Total C (%)		1.0	(0.4)	3.7	(0.7)
RIP[1] ($cmol_c\ kg^{-1}$)		332	(76)	45	(13)
pH (KCl)		6.9	(0.2)	4.6	(0.1)
Exchangeable cations[2] ($cmol_c\ kg^{-1}$)	K^+	0.85	(0.05)	2.02	(0.02)
	Ca^{++}	1.43	(0.57)	3.65	(0.35)
	Mg^{++}	1.34	(0.03)	6.39	(0.17)

[1] RIP = radiocaesium interception potential
[2] initial values (May 1996)

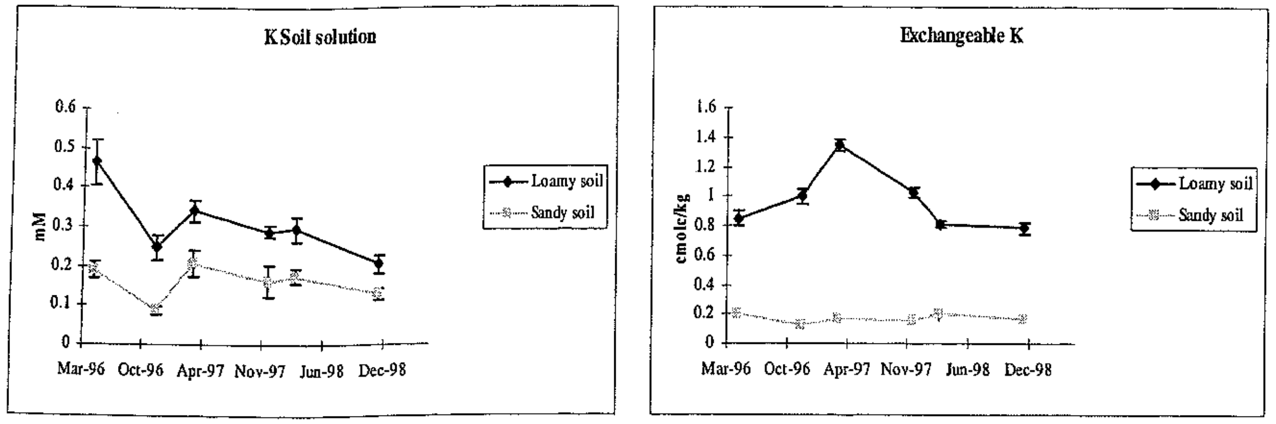


Figure 1: Evolution of K concentration in the soil solution of the two soil types (left) and evolution in exchangeable K of the two soil types (right) during the time of the experiment

Figure 2 shows the evolution in K concentration at actual humidity during one growing season (1998). The potassium concentration is better buffered in the loamy than in the sandy soil. Especially in the beginning of June and in August, a decrease in soil solution K in the sandy soil is found. Increasing or decreasing K concentrations could not be related to changing soil humidity ($R^2 = 0.11$ for both soils; data not shown).

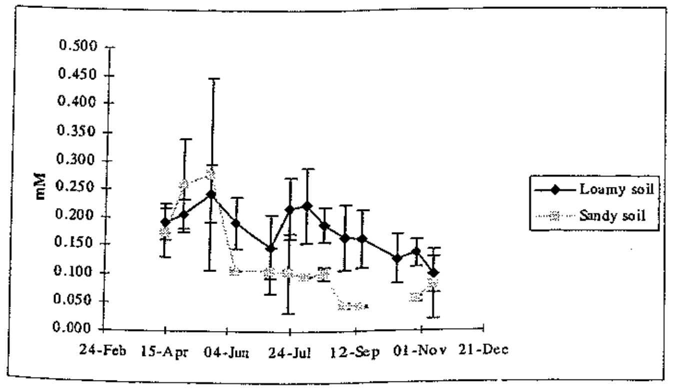


Figure 2: K concentration in the soil solution of the two soil types during the growing season 1998 at momentarily soil humidity

3.1.3.2 Biomass production

The relations between stem length or diameter and stem weight could be described by: stem weight = $a*x^b$, with x stem length for the R_2S_1 plants and stem diameter for the R_3S_2 plants. Correlations (R^2) varied between 0.85 and 0.97 for length/weight relations and between 0.97 and 0.99 for diameter/weight relations. Only in December 1998, a polynomial function of the second degree ($a + b*x + c*x^2$) gave a better fit than a power function. Also branch and leaf biomass are estimated based on shoot length or diameter. Correlations were between 0.79 and 0.97.

Under the experimental conditions, woody biomass production was similar for both soil types. Plant growth was characterised by a rapid biomass production in the beginning of the growing season which slows down afterwards (Figure 3). 1.0 and 1.4 t of dry wood per hectare were produced during the establishing phase of the culture (R_1S_1 plants) on the loamy and the sandy soil, respectively. In December the shoots were cut back and stools resorted the following growing season.

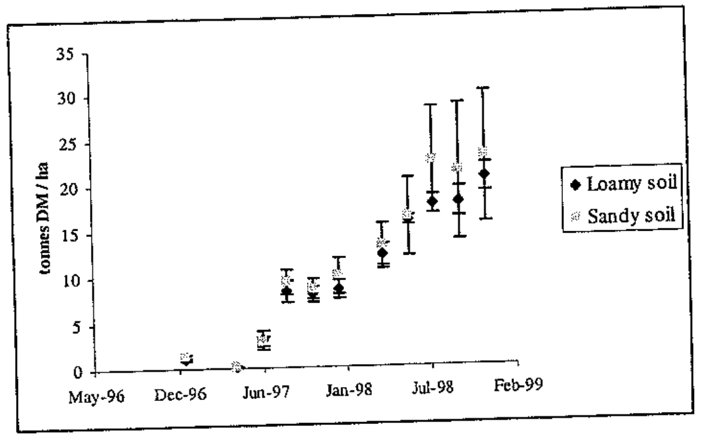


Figure 3: Biomass production in a willow SRC on experimental plots (dots are means and bars are standard deviations of 4 plots per soil type)- biomass values are recalculated for the density at the end of 1998

R_2S_1 plants produced 8.5 t dry wood ha^{-1} on the loamy soil and 10.0 t ha^{-1} on the sandy soil. Variations between the experimental plots did not exceed 20 %. During the third growing season (R_3S_2 plants) biomass production between the experimental plots on the sandy soil varied much more (> 40 %). Total standing biomass was 20.6 t ha^{-1} for the loamy soil and 22.9 t ha^{-1} for the sandy soil. Woody biomass production during the last growing season accounted thus for 12.1 t and 12.9 t ha^{-1}, respectively.

3.1.3.3 Evolution of radiocaesium and potassium in willow SRC throughout the growing seasons

Data for the willows grown on the sandy soil during the second and the third growing season are discussed in detail. The final balance will be compared with the SRC on the loamy soil.

Increase of radiocaesium accumulation in the biomass (Figure 4) is comparable with the biomass increase during the first half of the growing season (see earlier). However, while standing biomass remains more or less constant in autumn, the total amount of radiocaesium accumulated in the above-ground plant parts decreases. Indeed, part of the radiocaesium incorporated in the above-ground plant parts is retranslocated to the below-ground parts (difference between maximal content during the growing season and the final amount in the wood, litter and throughfall water).

As illustrates Figure 4, retranslocation patterns for radiocaesium and K are similar for both growing seasons. During autumn of the second growing season (R_2S_1 plants) 14.6 % of the maximal amount of radiocaesium incorporated in the above-ground biomass (October) and 12.2 % of the maximal potassium content (August) were retranslocated. Retranslocation figures for the third growing season (R_3S_2 plants) were higher: 43.6 % for radiocaesium and 56.2 % for K contents.

Contrary to the small amount retranslocated, a substantial part of the radiocaesium and K taken up by the R_2S_1 plants was returned to the soil by litter fall. This was due to an extremely dry period in August 1997 (with insufficient water supply) which caused rapid leaf fall. Plants did not have the opportunity to retranslocate the nutrients to wood or roots before leaf fall. More than half of the total litter biomass in 1997 fell in August, while in 1998 litter biomass fallen in August accounted only for 6 % of total litter biomass.

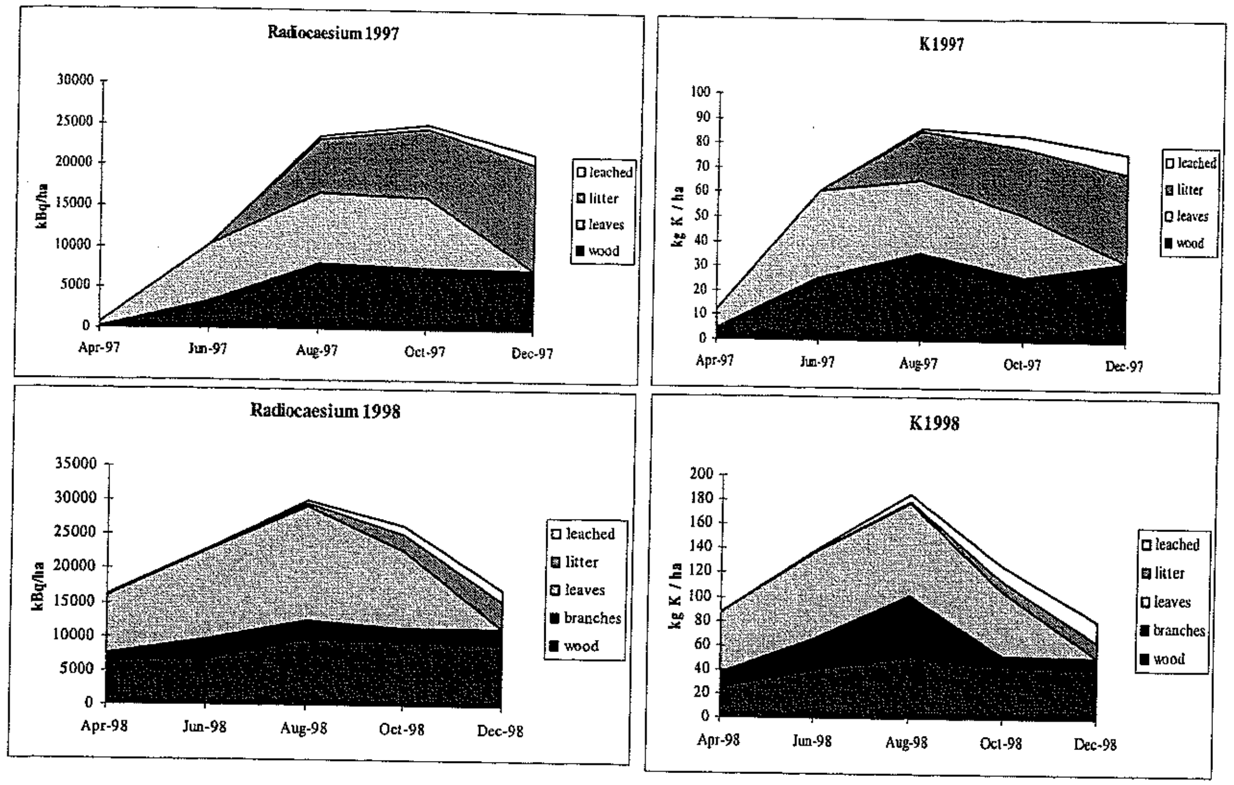


Figure 4: Evolution in radiocaesium and potassium contents in above-ground plant parts in a willow SRC on a sandy soil

The radiocaesium and potassium balance at the end of 1998 for the total plant (above- and below-ground plant parts) was as follows: the R_3S_2 plants (roots + wood) contained 19.6 10^6 Bq radiocaesium ha^{-1}, of which 9.7 10^6 Bq (~50 %) was found in the wood (stems + branches). Below-ground plant parts (cuttings + roots) contained as much as 9.9 10^6 Bq ha^{-1}. ENT accumulation in wood and below-ground plant parts during 1998 [X_i-X_{i-1}, with X the radiocaesium content in the respective plant part and i-1 and i two subsequent years] was 3.6 and 0.05 10^6 Bq ha^{-1}, respectively (Figure 5). Below-ground plant parts seemed thus to reach an equilibrium state. 1.7 10^6 Bq ha^{-1} was leached from the foliage during the growing season and 3.8 10^6 Bq ha^{-1} returned to the soil with litter fall. Total net uptake during the growing season equalled 9.2 kBq ha^{-1} and net accumulation accounted for 3.6 kBq ha^{-1}. Efficiency of radiocaesium incorporation in the plant material accounted thus for 40 % of the uptake.

The amount of K contained in the plants at the end of 1998 was principally incorporated in the wood (50.6 kg K ha^{-1}). Less than half of this was found in the below-ground plant parts (21.8 kg ha^{-1}). For radiocaesium, the largest part was found in roots + cuttings. The net accumulation during the 1998 growing season accounted for 40.7 kg K ha^{-1} of which still 41 % occurred in the below-ground plant parts. 17.7 kg ha^{-1} was leached from the foliage and 12.5 kg ha^{-1} returned to the soil through litter fall. Efficiency of K incorporation was 57 % for the R_3S_2 plants.

The higher accumulation of radiocaesium in the below ground plant parts compared to potassium as found for the willows, was also found for other plant species. The reasons for this difference are not yet clear, however. Erdei and Trivedi (1991) supposed that a selective barrier at the xylem vessel prevents radiocaesium transport to the shoots. Buysse *et al.* (1995) showed that is was not the xylem transport, but a limited capacity to withhold Cs in the shoots (limited uptake of Cs in the vacuoles) that may advance the radiocaesium accumulation in the roots.

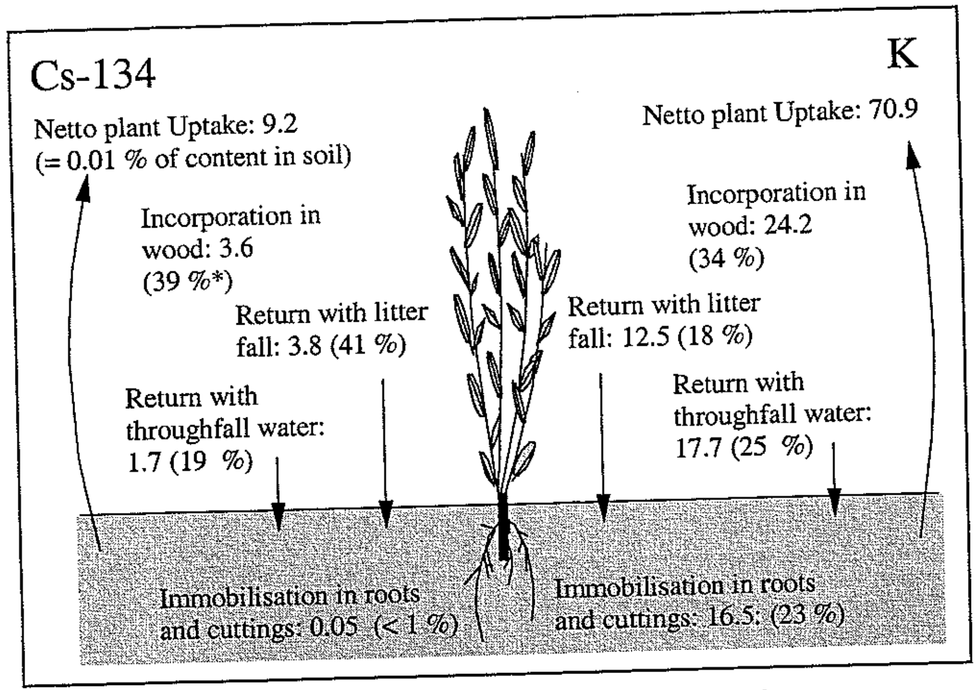


Figure 5: Net radiocaesium (10^6 Bq ha^{-1}) and potassium (kg ha^{-1}) uptake and partitioning of R_3S_2 plants on a sandy soil * *% of total radiocaesium or K contents immobilised in wood at the end of the growing season*

Radiocaesium and potassium are returned to the soil by two processes: leaching from the foliage by throughfall water and litter fall followed by litter decomposition. The contribution of throughfall to the return of radiocaesium was smaller than for potassium (31 % vs. 59 %). However, the seasonal pattern of foliage leaching was similar for both elements (Figure 6). The leaching is highest in autumn during leaf senescence. This is in accordance with observations of different authors (Witkamp and Frank, 1964; Tukey, 1970; Eaton *et al.*, 1973; Parker, 1983) and may be due to the ageing of the leaves. The leached potassium is supposed to originate from the internal leaf tissue and to be exchanged by protons or ammonium cations deposited on the leaf surface (Mecklenburg *et al.*, 1966; Lovett and Lindberg, 1984; Marques, 1996).

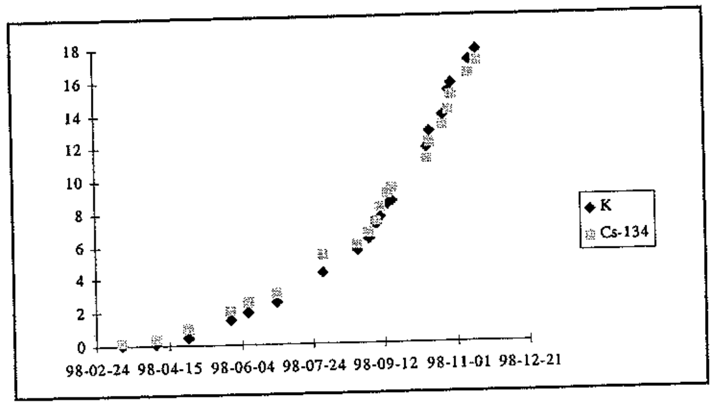


Figure 6: Cumulated radiocaesium (10^5 Bq ha^{-1}) and potassium (kg ha^{-1}) in throughfall under the willow canopy (R_3S_2 plants) in the SRC stands on the sandy soil

The lower leachability of radiocaesium compared to potassium is corroborated during litter decomposition (Figure 7). During the decomposition test, the biomass of the litter did not change significantly, except for the last two samplings (data not shown). After 7 weeks already, the concentration of both elements seemed to have reached an equilibrium state. However, still 38 % of the initial radiocaesium concentration was found and only 5 % of the initial potassium concentration. Only at the end of the experiment, the concentrations decreased again. Also Witkamp and Frank (1970) and Clint *et al.* (1992) found that potassium concentration decreased faster in decomposing litter than did radiocaesium concentration. Although soil particles adhering to the litter may distort the biomass changes during decomposition, the nearly constant biomass during the experiment indicates that leaching is the more important process. However, Joergensen and Meyer (1990) claim that leaching follows a certain nutrient release by biological decomposition. This may explain the decrease in concentration in both elements at the end of the experiment, since also biomass decreased at that moment probably due to biological decompostion. Since the small mesh sizes inhibited macrofauna to enter the litter bags, litter decomposition is supposed to occur faster in the field. Indeed, in the experimental plots, litter of the previous year was hardly perceptible. Slapokas and Granhall (1991) showed that willow litter decomposed more rapidly the larger the mesh sizes were and attributed this to earthworm activity. Supposed that nearly all potassium and a large part of the radiocaesium comes free during the first months after falling (before plant growth starts again), the elements are not intercepted immediately by plant roots and radiocaesium can be fixed by the soil particles.

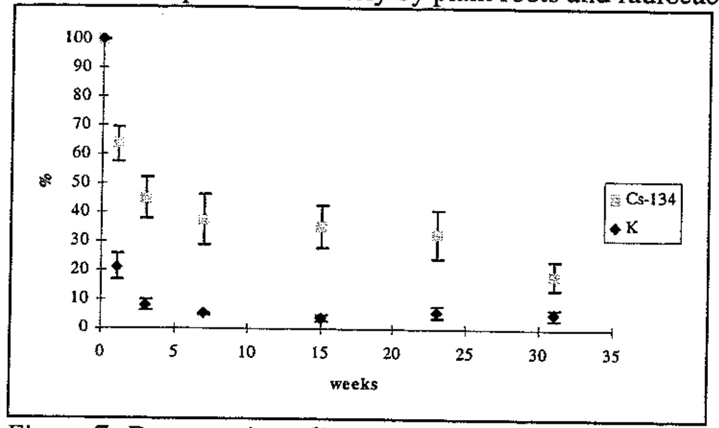
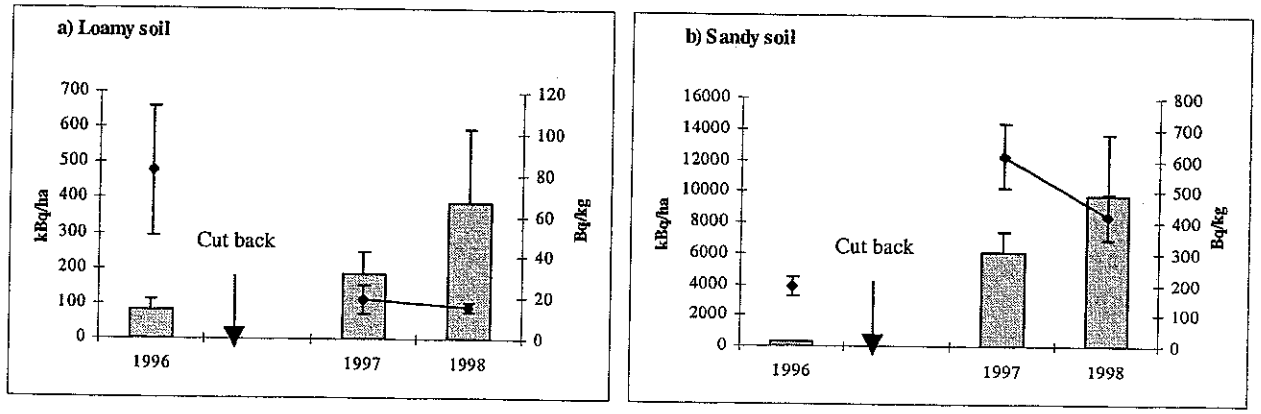


Figure 7: Decrease in radiocaesium and potassium concentration (% of initial concentrations in the litter) during litter decomposition

3.1.3.4 Evolution of radiocaesium accumulation in the wood with time

Radiocaesium accumulation in the willow wood depends both on biomass production and on evolution of radiocaesium concentration in the wood. Since radiocaesium concentrations in the wood is not constant during the three years studied, net accumulation is not proportional to biomass production (Figure 8). For willow SRC on the loamy soil net accumulation in the wood accounted for 80, 183 and 204 kBq ha^{-1} for the three growing seasons, respectively. For the sandy soil, 260, 6048 and 3643 kBq ha^{-1} was accumulated in the consecutive years.


a) Loamy soil

b) Sandy soil

Figure 8: Evolution in radiocaesium concentration (squares and lines) and radiocaesium content (bars) in the wood of willows (error bars are standard deviations, n=4)

While the evolution in biomass production is similar for the two soil types (see earlier), the evolution in radiocaesium accumulation differs due to different evolutions in radiocaesium concentration. The large decrease in radiocaesium concentration from the first to the second year for plants grown on the loamy soil may be due to a rapid fixation process of radiocaesium on the clay minerals after contamination. On the sandy soil, this process may have been less important (lower % of clay minerals, Table 1). On the contrary, radiocaesium seemed to be more available for the plants on the sandy soil, since radiocaesium concentration in wood increased from the first to the second growing season. This increase may be explained by a decrease in K concentration in the soil solution in the beginning of the second growing season during rapid plant growth and before fertilisation. Because all above-ground plant biomass is newly formed in 1997, the necessary K could not be supplied by what was already in the wood and K concentration in the soil solution may have decreased. It is well known by now that a decrease of K in the soil solution increases radiocaesium uptake (Smolders *et al.*, 1996). The decomposition of the litter from the previous year may have contributed to the higher uptake on the sandy soil. Indeed, radiocaesium returned to the soil by litter fall during the first growing season accounted for 3102 kBq ha^{-1} on the sandy soil, while this was only 340 kBq ha^{-1} for the loamy soil. After analysis the litter was put on the experimental plots mid January. As seen in the litter decomposition experiment, part of the litter was probably decomposed and radiocaesium set free and hence partially fixed (according to radiocaesium soil solution / soil particles equilibria) by the time the willows were resprouting. Part of the litter was decomposed during plant growth and the caesium set free may have been directly available for the plants.

On the loamy soil, R_3S_2 plants (1998) accumulated more radiocaesium than did R_2S_1 plants (1997), while they accumulated less on the sandy soil. Indeed, radiocaesium concentration in the wood of plants grown on the loamy soil remained constant from the second to the third growing season, while however, not significantly, the radiocaesium concentration in wood of plants grown on the sandy soil tended to decrease. Radiocaesium concentrations in the wood at the end of the third growing season were 16 Bq kg^{-1} and 420 Bq kg^{-1} for the plants grown on the loamy and the sandy soil, respectively (soil contamination 8 10^{6} Bq m^{-2}). This is lower than the exemption limit for fuel wood put forward in the CIS which amounted to 740 Bq kg^{-1} dry wood (Szekely *et al.*, 1994). Radiocaesium TFs$_{wood}$ are 2 10^{-6} m^2 kg^{-1} for willows on the loamy soil and 5 10^{-5} m^2 kg^{-1} for willows on the sandy soil at the end of 1998. Supposed that the radiocaesium concentration will not increase during the last year of the cutting cycle, the wood may be burned for energy production. Consequently, willow SRC can be established on a sandy soil (with similar soil properties as the one studied) contaminated up to 14 MBq m^{-2}, or a loamy soil contaminated up to 370 MBq m^{-2}.

3.2 Radiocaesium accumulation in willows of different ages and grown on different soil types

The major objective of the extensive sampling at farmer plots in Sweden was to have a sufficiently large data set of coppice TF linked to different soil types, coppice varieties and age categories to broaden the basis for estimating radiocaesium levels in the coppice wood.

Existing willow SRC plots were sampled once in central Sweden (north of Uppsala) between November 1997 and April 1998. In this area deposition from Chernobyl was one of the highest for Sweden. The plots were of different ages (all established after 1986), different clones and different soil type. Ten shoots per plot were cut, the wood was ashed to concentrate the radiocaesium activity and ^{137}Cs and ^{40}K in the ashes were counted in a HPGe-detector. The soils were analysed as described for the soils of the experimental plots. The sampled plots differed in their soil characteristics (Table 2). Few sandy soils were sampled (Trödje, Tierp 1, Tierp 2 1M). Most soils were very clayey differing, however, in organic matter content and/or nutrient status.

Soil-to-wood TFs ranged over three orders of magnitude: from 2.4 10^{-6} to 1.4 10^{-3} m^2 kg^{-1} (Table 2). However, omitting the plots in Trödje, the variation in TF between the plots was not very large. Moreover, notwithstanding very different values for the radiocaesium interception potential (RIP) , TF values between some plots did not differ much (e.g. Viksta 1 and Tierp 2 1G). Results from a simple regression analysis were consequently not satisfactory. RIP value and clay content seemed the most important factors affecting the TF, but correlations were never significant (data not shown). Neither shoot age of the plants nor biomass production did determine the TFs. Differences between clones could generally not be detected since only at one plot (Viksta 1) two different clones could be sampled. At this plot, the clone RAPP accumulated significantly less radiocaesium than did clone 78-183.

The uptake of radiocaesium is a combination of two processes: the dynamic equilibrium between radiocaesium sorbed on soil particles and radiocaesium in the soil solution (K_D) and the uptake of radiocaesium by the plant from the soil solution (Smolders *et al.*, 1997). Therefore, the transfer factor can be written as

$$TF = CF/K_D, \text{ or } \log(TF) = \log(CF)-\log(K_D) \tag{2}$$

with CF (concentration factor) the ratio of radiocaesium in the plant [Bq kg^{-1}] to the radiocaesium in the soil solution [Bq L^{-1}]. Radiocaesium concentrations in the soil solution and thus CFs can be calculated by taking ageing into account (Absalom *et al.*, 1999). The log(CF) can be estimated based on the K concentration in the soil solution (mK) [b_0-b_1*log(m_K), Figure 9]. The decreasing CF with increasing mK is also found in different hydroculture experiments for different crops (Smolders *et al.*, 1996; Buysse *et al.*, 1996). Especially at very low K concentrations, the uptake of radiocaesium increases very sharply. The CF decreased more than proportionally to the reciprocal of the K concentration.

Table 2: Plant variety, age, TF and soil characteristics for the different willow plots in Sweden.

Site	Variety	Age RxSy	TF m^2 kg^{-1}	Cont. kBq m^{-2}	RIP cmol$_c$ kg$^-$	CEC cmol$_c$ kg$^-$	Exch. K Cmol$_c$ kg$^-$	m_K m*M*	pH (KCl)	OM %	Texture (%, µm) < 2	 2-20	 20-200	 >200
Viksta 1	Rapp 183	R_5S_4 R_6S_2	8.2 10^{-5} 3.8 10^{-5}	22	1377	20.1	0.34	0.12	6.19	3.9	30	22	38	9
Viksta 2	183	R_6S_2	3.1 10^{-5}	22	1086	21.7	0.37	0.20	5.10	5.1	32	23	43	2
Viksta 3	183	R_6S_2	5.4 10^{-5}	22	1091	25.0	0.36	0.09	5.02	4.8	33	25	39	3
Tierp 1	183	R_6S_2	3.2 10^{-5}	30	303	8.1	0.27	0.38	5.10	4.3	6	5	86	3
Tierp 2 1G	Rapp	R_5S_4	1.4 10^{-5}	30	811	9.5	0.24	0.19	5.79	2.3	15	13	70	2
Tierp 2 1M	Rapp	R_5S_4	1.3 10^{-5}	43	182	10.6	0.15	0.31	5.41	7.3	4	5	30	54
Björkl. 2	183	R_8S_2	3.2 10^{-5}	33	1047	14.4	0.23	0.15	6.20	3.1	22	33	38	7
Björkl. OR	Rapp	R_6S_2	2.4 10^{-6}	42	986	22.4	0.58	0.16	5.01	3.2	34	30	34	2
Björkl. 1	183	R_7S_2	9.0 10^{-6}	30	773	22.2	0.21	0.34	4.66	9.1	31	26	42	1
Österfär.	183	R_7S_6	2.8 10^{-5}	15	686	8.6	0.24	0.32	4.24	3.0	14	16	48	22
Trödje 1	183	R_4S_4	8.9 10^{-4}	90	113	3.9	0.11	0.48	5.20	2.9	3	2	23	71
Trödje 2	183	R_4S_4	1.4 10^{-3}	90	112	4.5	0.08	0.29	6.59	2.9	3	2	23	71
Trödje 3	183	R_4S_4	1.0 10^{-3}	90	116	3.8	0.1	0.39	6.58	2.9	3	2	23	71
Trödje 4	183	R_4S_4	5.8 10^{-4}	90	103	3.1	0.18	0.95	5.25	2.9	3	2	23	71

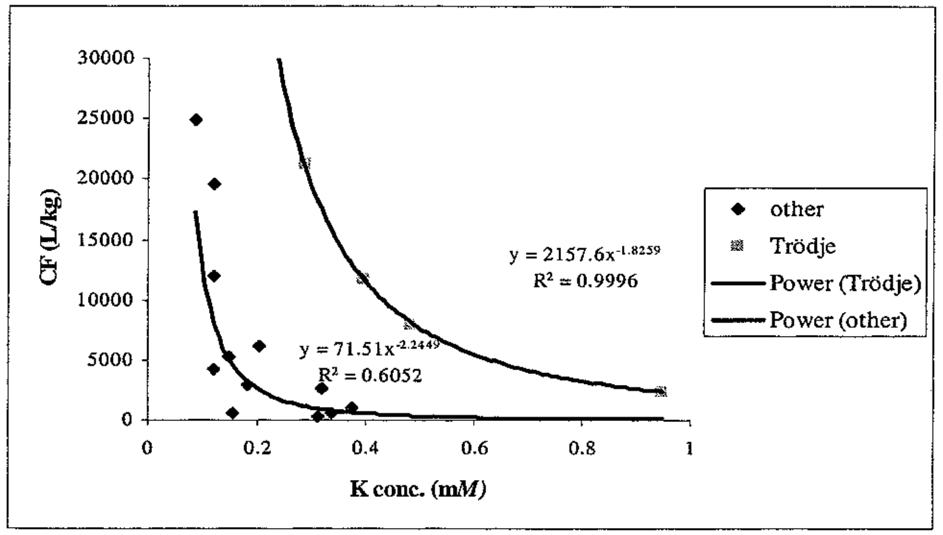


Figure 9: Radiocaesium CFs ([Bq kg^{-1} dry wood]/[Bq L^{-1} soil solution]) in relation to the K concentration in the soil solution (mM) for the plots in Trödje and for the other Swedish plots

From Figure 9 it is clear that the Trödje plots differ from the other plots. Trendlines (power functions) in the figure are best fits for both series. For the same K concentrations in the soil solutions, higher CFs are found for the plots in Trödje. Ageing and hence the CF, may have been overestimated for the sandy Trödje plots. However, the soils of Tierp 1 and Tierp 2 1M also have low clay contents, comparable to the results in Trödje. Comparatively high NH_4^+ concentration in the soil solution at Trödje may also have increased the CF at comparable K levels (Minotti *et al.*, 1965). This hypothesis could not be checked since soils were dry when analysed. A higher organic matter content could neither explain the higher CF estimated for Trödje soils. Finally, the difference may be due to a difference in clay mineralogy of the soils and thus different sorption/desorption characteristics. Indeed, Trödje is located more North than the other plots and may have different parent material. This parameter was not investigated.

From the predicted CFs, TFs can then be calculated following eq. 2 based on the K_D value and the m_K according to the formula [$\log(TF)=b_0-b_1\log(m_K)-\log(K_D)$]. From a non-linear estimation ($b_0=8.23\pm0.33$ and $b_1=1.67\pm0.21$), this function explains 63.4 % of the variation between the plots. However, when we leave out the data of Trödje, it only still explains 13 % of the variation.

3.3 *Case study in Belarus*

For two major reasons, field trials were established in May 1997 in Belarus on former agricultural land, left uncultivated after the Chernobyl disaster. Firstly, yield and most probably also radionuclide uptake and distribution are highly climate and soil dependent. Results obtained in other trials (Belgium, Sweden) would therefore not necessarily befit the Belarus situation. Secondly, the contamination in Belarus is of another nature (more liable to the presence of hot particles than in Sweden) and probably more aged (due to gradual fixation of radiocaesium by the soil particles) than in the trials set-up in Belgium.

3.3.1 Materials and methods

At two locations, Savichy and Masany (Figure 10) trials were established on a sandy and a peaty soil. Four clones, selected for high yields, frost and pest resistance (Vandenhove *et al.*, 1998) were planted in 4 replicates at all four sites. The four clones selected are Rapp (*Salix viminalis*), Orm (S. *viminalis*), Jorr (*S. viminalis*), and Björn (*S. viminalis x S. schwerinii*).

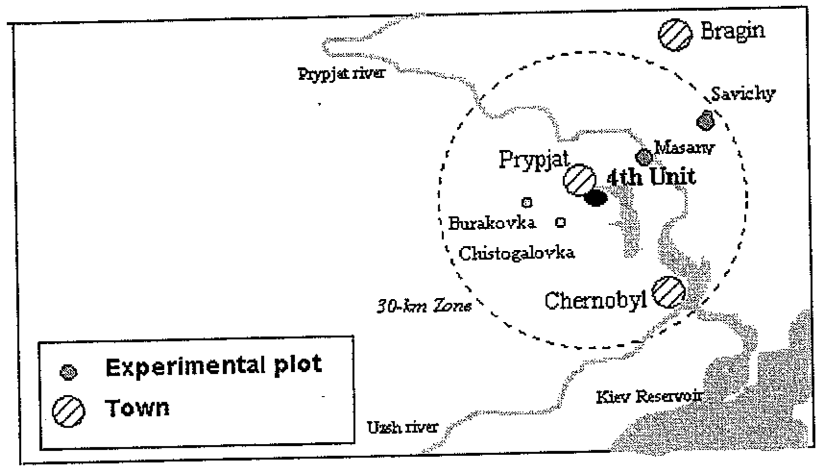


Figure 10: Locations of the Belarus test fields

The soils at Savichy are characterised as soddy-podzolic sandy soil on glacial associated sand superseded by loose sand and as a low-land type peaty-marsh soil on medium-thick well decomposed sedge-reed-woody peat. Thickness of peat is 1-2 m. The Masany sandy soil is a soddy-podzolic sandy, sandy-loam on alluvial gleyic shallow-grainy sand. The depth of the humus horizon is 20-25 cm. The ground water table (May 5) is -1.2 m. The Masany peat bog peaty soil is located in lowland meadow. The ground water table (May 5) is at -0.25 m.

The experimental site at Savichy was disked and cleaned from weeds. At Masany, a 40 by 40 cm square was cleaned from weeds and the coppice cuttings planted. Sites were not weeded afterwards. No fertiliser was applied.

At the start of the experiment the soil of the Savichy test sites was analysed for CEC, total carbon (loss through ignition), texture, apparent density and total ^{137}Cs and ^{134}Cs. The results are presented in Table 3. Every year at the end of the growing season, the soil of each block (five 25-cm cores per block, homogenised and dried) was analysed for pH (KCl), exchangeable K, Ca, Mg and ^{137}Cs (extraction with 1 N NH_4Ac). For Masany a less thorough soil characterisation was performed. At the end of the 1997 growing season, the whole plot was harvested by cutting back the willows. At the end of each growing season (November 97 and 98), stems of 10 plants per plot were cut and homogenised. A subsample was oven dried, ground and analysed for ^{137}Cs activity and K, Mg and Ca content in two-fold (for procedure, Chapter 3.1).

During the growing season measurements were performed for the growth modelling. All growth related discussions are dealt with in Chapter 5.

3.3.2 Soil characteristics and radiocaesium uptake

Crop performance on the sandy soils was deplorable (at Masany the willow died during the first year; at Savichy plants did hardly grow) and at Masany-peaty growth was limited due to the competition with weeds. At Savichy peaty, the willows were performing well.

Table 3: Some soil characteristics of the sandy and peaty soil at Savichy (averages between blocks; standard deviations between brackets)

"Permanent" soil characteristics		**Savichy peaty**	**Savichy sandy**
^{137}Cs (kBq m^{-2})		19385 (4784)	1438 (308)
^{137}Cs (Bq g^{-1})		210 (53)	4.05 (970)
CEC ($cmol_c$ kg^{-1})		41.7 (1.2)	1.03 (0.42)
RIP $cmol_c$ kg^{-1})		38.8 (13.6)	17.5 (5.5)
Total C (%)		48.60 (0.87)	1.47 (0.24)
Apparent density (kg L^{-1})		0.37 (0.01)	1.42 (0.02)
Texture	< 10 µm		6.5 (0.6)
	10-50 µm		8.8 (0.9)
	50-250 µm		72.6 (3.2)
	250-500 µm		11.4 (3.7)
	>500 µm		0.7 (0.1)
More variable soil characteristics			
1998			
Exchangeable cations ($cmol_c$ kg^{-1})	K	0.55 (0.09)	0.043 (0.006)
	Ca	33.35 (2.19)	0.68 (0.38)
	Mg	3.73 (0.58)	0.19 (0.03)
pH		4.5 (0.1)	3.9 (0.2)
Exchangeable ^{137}Cs (%)		1.27 (0.26)	3.03 (0.77)
1997			
Exchangeable cations ($cmol_c$ kg^{-1})	K	0.54 (0.08)	0.048 (0.013)
	Ca	37.9 (1.4)	1.00 (0.29)
	Mg	3.72 (0.37)	0.15 (0.01)
K in soil solution (mM)		0.256 (0.134)	0.092 (0.046)
pH		4.4 (0.1)	3.9 (0.2)
Exchangeable ^{137}Cs		1.48 (0.29)	2.98 (0.68)

For Masany, the contamination level was 3156±1070 kBq ^{137}Cs m^{-2} or 44±15 Bq g^{-1}. The soils are rather poor in potassium: only about 1 (peaty) to 5 (sandy) % of the regular cation exchange complex is occupied by potassium (Table 3). Soils with a low potassium status are rather liable to high radiocaesium transfer as is the low pH of both soils. Notwithstanding, exchangeable Cs-levels are low: 3 % or less. Values for exchangeable cations and exchangeable Cs did hardly change from one growing season to the other.

Wood nutrient composition was only determined at the end of the second growing season for the sandy and peaty soil at Savichy. Given the deplorable condition of the willows on the sandy soil, these data are nor presented. For the peaty soil the concentrations were 2.46±0.43, 2.94±0.57 and 0.94±0.10 g kg^{-1} for K, Ca and Mg, respectively. These contents are comparable with the values observed for the Belgian lysimeters (Vandenhove *et al.*, 1998), indicating that the willows do not show nutrient deficiency.
Radiocaesium TFs are up to a factor of 1000 higher that the TFs recorded in Sweden and on the Belgian lysimeters (Figure 11). They range between 0.24 to $2.60*10^{-3}$ m² kg^{-1} on the sandy soil and between 0.49 and 2.21 $*10^{-3}$ m² kg^{-1} on the peaty soil at Savichy. At the Masany peaty soil the TFs range between 0.18 and

$0.74 * 10^{-3}$ m² kg^{-1}. It is also clear from Figure 12 that due to the large variation there is no significant difference in TF between the different willow clones.

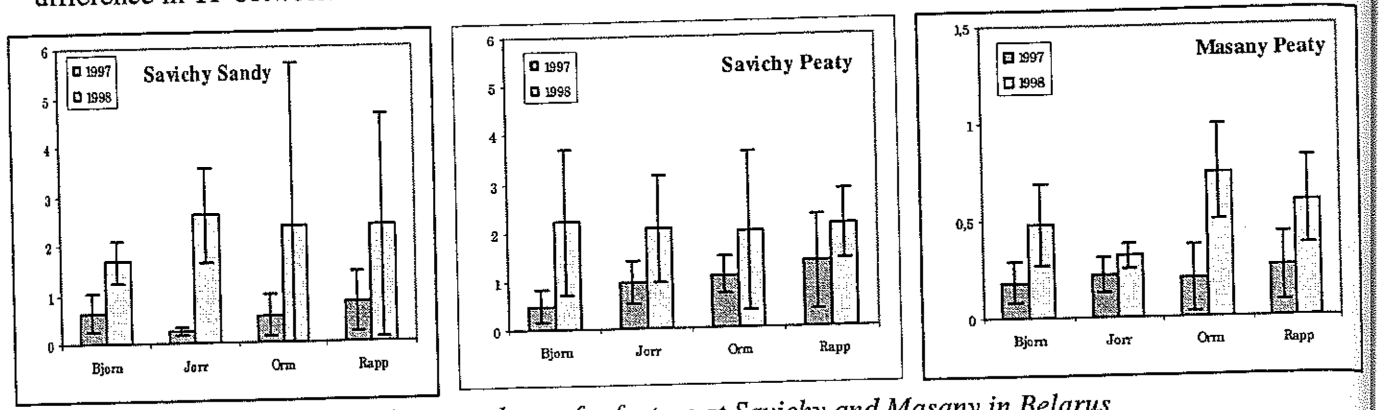


Figure 11: Radiocaesium soil-to-wood transfer factors at Savichy and Masany in Belarus

The TFs on the sandy and peaty soil at Savichy are comparable. The soil K-status is similar for both soil types but the RIP is a factor of two higher for the sandy soil and yet, the amount of radiocaesium available is a factor two higher on the sandy soil. Since no additional soil measurements were done at Masany, it is difficult to explain the fourfold difference in TFs between the two peaty soils.

The high TFs obtained are comparable with TFs at the Swedish Trödje sites (0.58-1.4 10^{-3} m² kg^{-1}), where soils also showed low RIP values (103-113 µeq g^{-1}, Table 2) close to RIPs at Savichy (175-333 µeq g^{-1}).

TFs tend to increase with a factor two from the first to the second growing season, in accordance with the observations for the Belgian lysimeters (sandy soil). The threefold increase in radiocaesium concentration in the wood recorded for the willows grown on the experimental plots in Belgium (sandy soil) was explained as follows. Firstly, by a rapid plant growth in the beginning of the growing season and a soil which could not supply the high K-demand resulting in a depletion of soil solution K and hence an increasing Cs-uptake; secondly, by the radiocaesium released from decomposing litter. The Belgian lysimeters were fertilised in the year after cut back (i.e. the second growing season) and radiocaesium concentrations in the wood decreased during the third growing season. From observations we could also assume that the coppice system became auto-sufficient in K from the third growing season onwards (2nd year after cut-back). This observation is of importance for the Belarus scenario. Sites were not fertilised and hence we still may expect a slight increase in TF during the 3rd growing season. If, on the other hand, it is assumed that, as was observed on the Belgian lysimeters, the coppice system does not need any extra K-input due to internal recycling of K, we may expect the TF not to increase anymore during the next growing seasons.

The hypothesised extremely low K-concentrations in the soil solutions in Belarus sandy and peaty soil and the likely presence of NH_4^+ due to decomposition of the organic matter in the peaty soil, may possibly clarify why the TFs in Belarus are a factor 100 higher than on the sandy soil in Belgium. This in spite of the fact that in Belgium the contamination was rather recent (1996), compared to Belarus (1986) and the radiocaesium was assumed to be less available in the latter scenario. It might well be that in the peaty (and sandy) soil in Belarus, there are no Cs-fixing clay minerals present.

Given the high TF but more importantly, due to the extremely high deposition levels at the test sites, the concentration of Cs in the wood (Table 4) was higher than the level acceptable for fuel wood which is set at 740 Bq kg^{-1} in Belarus. If we would consider an average transfer factor of $2*10^{-3}$ m² kg^{-1} during the second growing season and assuming this TF would not increase anymore, willows can only be safely cultivated on sandy or peaty soil contaminated up to 370 kBq m^{-2}.

Table 4: Concentration (Bq ^{137}Cs kg^{-1}) in the willow wood

	1997	**1998**
Savichy sandy	756 (563)	3015 (2363)
Savichy peaty	14180 (8186)	36657 (2363)
Masany peaty	598 (307)	1711 (923)

3.4 Radiocaesium uptake by other bioenergy crops

Apart from SRC a number of other cultures are discussed to some extent in terms of their aptness as alternative land use of contaminated soil.

Reforestation of contaminated arable land is one possible remediation option. Initial investments are comparable to the coppice plantation costs but returns only showing after 60 years or more, except for the limited revenue from the thinning. If forests would be planted widely spaced so that thinning is not needed in order to reduce workers' exposure, even no such intermittent revenue is to be expected.
At present, no information is available on transfer factors or radiocaesium fluxes in forests which were planted after the Chernobyl accident. For the comparison of TFs and fluxes between willow vegetation system and forests we will have to rely on data of forests which were in place at the time of the accident.

From the soil-to-wood and soil-to-bark TFs, it is obvious that in general TFs to coniferous and deciduous wood are a factor 100-1000 higher than for willows (Table 5). Only the high TFs observed in willows in Trödje and Belarus plots are comparable to the TFs for forests. It should however been stressed that the TFs in forests are not purely soil to plant TF since the foliage intercepted part of the radiocaesium.

Table 5: Radiocaesium transfer factors in coniferous and deciduous trees (following Ponomarev et al., 1997 *and Zadbudko et al.*, 1995)

Tree species		**TF$_{soil \rightarrow wood}$ (m^2 kg^{-1})**	**Tree species**		**TF$_{soil \rightarrow wood}$ (m^2 kg^{-1})**
Fir	Wood	$6.7\ 10^{-4} - 2.0 \cdot 10^{-3}$	**Aspen**	Wood	$2.8 \cdot 10^{-3}$
	Bark	$3.0\ 10^{-3} - 1.5 \cdot 10^{-2}$		Bark	$2.3 \cdot 10^{-2}$
Pine	Wood	$8.3 \cdot 10^{-4} - 1.7 \cdot 10^{-3}$	**Birch**	Wood	$1.7 \cdot 10^{-3}$
	Bark	$1.0 \cdot 10^{-3} - 9.0 \cdot 10^{-3}$		Bark	$7 \cdot 10^{-3}$
Oak	Wood	$1.8\ 10^{3} - 2.2 \cdot 10^{-3}$	**Alder**	Wood	$1.2 \cdot 10^{-3}$
	Bark	$6.8 \cdot 10^{-3} - 1\ 10^{-2}$		Bark	$9 \cdot 10^{-3}$
Lime	Wood	$8.5 \cdot 10^{-4}$			
	Bark	$4.5 \cdot 10^{-3}$			

A comparison was made between the annual radiocaesium accumulation in wood of willows grown on the sandy soil at the experimental plots in Belgium and in wood of *Pinus sylvestris* L. in a traditional forestry system [also grown on a sandy soil; soil contamination = 1.5 MBq m^{-2}; Thiry *et al.* (1999)]. Activity concentrations found in the wood of 17 years' old pine trees were nearly 4000 Bq kg^{-1} dry wood (excluding the most recently formed tree ring and bark). This gives a TF$_{wood}$ of 3 10^{-3} m^2 kg^{-1}, which is similar to the TFs presented in Table 5. With a biomass production of 14.8 m^3 ha^{-1} year^{-1}, and a wood density of 0.4, the pine trees have been accumulating radiocaesium at a rate of 23.1 MBq ha^{-1} year^{-1}. This accumulation is 5 times higher than for the last two years in the willow coppice system (lysimeter study, sandy soil), despite the about 7 times lower soil contamination level in the forest stand (Figure 12). For the scenario studied, we can thus conclude that annual radiocaesium accumulation in willow SRC wood is much lower than for a forest stand in the Chernobyl affected area.

It is very well possible that acid soil conditions and low K concentrations in the forest soil may have contributed to high soil-to-wood transfer in the pine forest. Further, though the pine stand was young in 1986, the trees have been contaminated by deposition of the Chernobyl fallout. The largest part of the radiocaesium intercepted by the foliage is leached of by the rain during the first year (Ipatyev *et al.*, 1998) and is found in the forest litter/humus where most of the total caesium deposited remains highly available for root uptake. In case the radiocaesium was deposited on the soil, caesium is less available for the trees since it is partially fixed by the soil particles. Further, the amount of radiocaesium transported after root uptake to the leaves/needles and returned to the soil as litter is only a fraction of what would have been found in the litter/humus in case of an interception scenario. Since it is known that in a forest ecosystem almost the entire radiocaesium cycling is confined to the humus layer (highest fraction of caesium taken up by roots is from the humus layer), it is very probable that the transfer factors to newly planted forests on land contaminated by the Chernobyl accident would be considerable lower than the TFs presented in Table

5. Information on real soil-to-plant transfer factors of forests installed on contaminated agricultural land will be available from the PHYTOR-project (Vandenhove *et al.*, 1999).

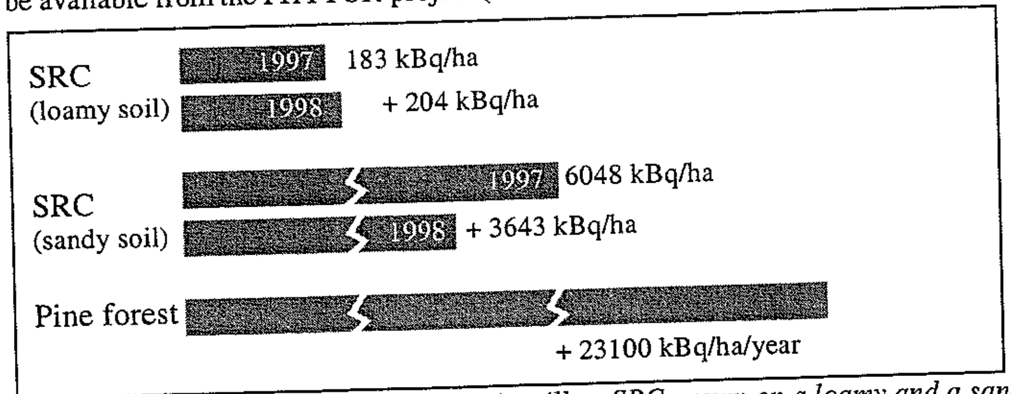


Figure 12: Radiocaesium accumulation in willow SRC grown on a loamy and a sandy soil (lysimeter study, Belgium) compared to a 17 years' old pine forests (Vetka, Belarus)

For the scenario presented in Figure 12, we could conclude that annual radiocaesium accumulation in willow SRC wood is much lower than for a forest stand in the Chernobyl affected area. Since also potential biomass production by willows is higher (12 t for SRC vs. 6 t ha^{-1} for forests), wood production on contaminated land in a SRC system seems to be promising. However, if the water reserve of the soil is low, as is the case for a sandy soil, the potential (no nutrient limitations) yield under Belarus conditions is only 5 t ha^{-1}. The results from the willow trials on the sandy soil at Savichy and Masany indicate, moreover, shown that actual yields may be considerably lower. For those sandy soils (low water reserve and nutrient status), re-forestation is a better option than a SRC system. On soils with a higher water reserve (e.g. loamy , peaty) SRC may be preferable. Both cultures are hence highly compatible.

From the literature, a range of TFs to a number of potential energy crops were assembled: to wheat and sugar beet for ethanol production and to rape seed for production of rape methyl esters (RME=diesel). TFs to green mass and roots are comparable to a factor 10 higher than TFs to SRC. TFs to the seeds are generally a factor of 5 smaller (Table 6).

Table 6: TF to different plant components of liquid-biofuel crops (TF for sandy soil)

Crop	**Plant component**	**TF, 10^{-3} m² kg^{-1}**
Spring wheat	leaves	0.23-0.42
	stems	0.23-0.36
	grain	0.08-0.16
Cereals	grain	0.0048- 0.71*
Winter wheat	straw	0.27-0.44
	seeds	0.08-0.18
Spring rape seed	stems and leaves	0.12 (0.46**)
	straw	0.017 - 1.4**
	seeds	0.03-0.04 (0.0006 - 0.5**)
Brassicaceae	seeds	0.037-3.4*
Sugar beet	root	0.48 #
Root crops	root	0.025 - 0.94*
Green vegetables	leaves	0.07 - 4.86*

Data from Grebenkov (1997), * from Nisbet *et al.* (1999), ** from Gopa 1996 and # from IAEA, 1994.

3.5 Fate of radiocaesium during biomass conversion

In case of a contamination scenario, it is important to have an idea about the fate of the radionuclides during the biomass processing and conversion into a useable (energy) end product. Emphasis is on fate of radiocaesium during valorisation of wood into heat and/or electricity by combustion (or comparable) techniques. Since the type of power plant and type of biofuel will affect the fate of radiocaesium, these aspects are discussed in some detail. Fate of radiocaesium in other conversion routes (combustion of straw and peat; wood pulping; conversion of rape seed into rape methyl ester and sugar beet and wheat into ethanol) will be discussed in lesser detail.

3.5.1 Biofuels, techniques and processes

Stem wood is used as raw material in the production of paper pulp, sawn wood and heat and electricity. Given the scope of the RECOVER project emphasis will be on the fate of radiocaesium during biomass combustion and gasification and less so to the fate of radiocaesium during the pulping process.

To reliably estimate the transfer from biofuels to ashes it is important to know the ash content in the fuel and the proportion of radiocaesium escaping with flue gases and condensation water. Since different constructions of district heating plants exist and different combustion techniques are in use, it is impossible to put forward a common fuel-ash transfer factor. Incomplete combustion of the fuel, resulting in varying carbon contents in the ash, different ash contents for different biofuels and varying amounts of radiocaesium escaping to the atmosphere, results in a broad range of ash enrichment factors (Cs in ash/Cs in fuel wood) of radiocaesium.

3.5.1.1 Combustion techniques

Fluidised bed combustion (FBC), grate firing and pulverised fuel firing (PF combustion) are among the most common combustion techniques (Steenari, 1998). In the FBC technique, the bed where the combustion takes place, is a mixture of fuel, ash and sand. Air brought in from below keeps the bed fluidised, thereby improving the heat transfer, and combustion is more or less complete at relatively low temperatures (800-900° C) and at low excess of oxygen. This is a common technique for larger heating plants with power ranging from 20 to 160 MW (Nutek, 1994). Several varieties of this technique have been developed, BFB (atmospheric bubbling bed), CFB (atmospheric circulating bed) and PFBC (pressurised fluidised bed combustion) (Steenari, 1998).

In grate fired boilers the fuel is combusted on a large grate where the combustion air is brought in from below. The grate is usually tilted where the fuel is fed to the upper part of the grate and the bottom ash collected in lower part of grate. The combustion temperature is about 1100-1200° C (Steenari, 1998). The technique is most common for small and medium-sized heating plants.

In PF combustion, the fuel consists of a dry powder that is brought into the burner together with the combustion air. In PF burners, a mixture of oil and biofuels can be used (Nordliner, 1989) and the temperature is around 1300-1500° C (Steenari, 1998).

Gasification is a promising technology for the conversion of solid fuel to combustible gases. The gas mixture (H_2, CO and CH_4) can be burnt in a generator for heat or electricity production. Biomass conversion in small-scale gasification plants seems particularly attractive for decentralised power production close to the biofuel sources and energy requirements, as may be the situation in Belarus.

3.5.1.2 Flue gas filtering systems

Filtering systems are used for removing impurities from the flue gases in heating plants. Examples of filters are cyclones, textile baghouse filters and electrostatic precipitators. Cyclones are effective for separating large particles from the flue gases. Part of the ash are large particles which are usually recirculated to the furnace while the smaller ash particles are rejected as a residue (Steenari, 1998).

The fly ash is collected in textile filters (e.g. baghouse filters) or electrostatic precipitators where the flue gases are passing an electric field and the ash is precipitated on one of the electrodes (Nordliner, 1989). The collection efficiency for both electrostatic precipitators and fabric baghouse filters are very high. The mean fly ash collection efficiency in three Finnish peat fired power plants ranged between 96.7 % and 99.0 % (Jantunen *et al.*, 1992). Radiocaesium collection efficiency is probably slightly lower since the affinity of radiocaesium is generally higher for smaller ash particles.

In the gasification plants, gas cleaning is often at low temperature: the gas leaving the generator is cooled down in a water scrubber. In the Belgian pilot gasification plant (se 3.5.2.2) The water, which entraps the dust particles and part of the tar, is filtered and recirculated. To dry the cleaned gas, it is forced through a filter and the tar containing filtrate is dried and brought back in the generator with the biofuel. The impurities usually end up in the liquid effluents

3.5.1.3 *Wood ash*

Ash composition depends on fuel type and combustion technique. Generally two types of ashes, fly and bottom ash, are produced. Bottom ash is the residue at the grate after combustion and consists of partly melted ash that is well burnt and has a relatively large particle size and density (Nutek, 1994). In a grate fired boiler the major part of the formed ash is fly ash but the variation is large. Fly ash is the part of the ash that is transported with the flue gases and contains a larger part unburned fuel than bottom ash and consists of smaller particles. Concentration of volatile elements is generally higher than in bottom ash (Trädbrändsle, 1994).

FBC ash is produced in fluidised bed burners. The ash is separated from the flue gases in the same way as fly ash. The main differences between fly ash from a grate fired burner and FBC fly ash are that FBC fly ash contain a less amount of unburned fuel and that it also contains bed material (sand) (Nutek, 1994). In a CFB unit about 50 % of the formed ash is filter ash while the other 50 % is bed ash.

During combustion a separation of lithophilic elements (boiling point temperature above 1500° C: Be, Mg, Ca, Sr, Ba, Ra, Ti, Cr, Mn, Fe, Ni, Cu, Al) and volatile elements (Na, K, Rb, Hg, Cd, Sn, Se, Te, Zn, Pb, As, Sb, Cl, Br, I, S, Mo, Cs) will take place (Bäverman, 1994). The fly ash matrix is composed of lithophilic compounds which are transported with the flue gases. When the temperature of the flue gases decreases, the volatile elements can be condensed and enriched at the surface of the fly ash particles. Since the surface area per unit mass is larger for small particles the concentration of volatile elements is usually higher in the fraction of small particles. The surface enriched elements are often easily soluble as they form salts with chloride, phosphate and sulphate (Bäverman, 1994).

Table 7: Ash content of different biofuels (after Steenari, 1998)

Fuel	% ash content
Pine barking waste	1,8
Spruce barking waste	3,4
Birch barking waste	1,6
Wood chips, unspecified	1,8 – 3,8
Straw, unspecified	2,2 – 4,0
Salix	1,8 – 2,3

Table 8: Inorganic element content (% W/W on dry matter) in wood and bark ash (after Steenari, 1998)

Element	Pine		Spruce		Birch	
	Wood	*Bark*	*Wood*	*Bark*	*Wood*	*Bark*
Na	0,06	0,4	0,06	0,2	0,06	0.1
K	4,0	20	4,0	22	5,0	14
Ca	6,0	52	8,0	50	7,0	30
Mg	2,0	7,0	1,0	6,0	2,0	5.0
P	0,4	6,0	0,7	5,0	0,8	4.0
Cl	1,0	1,0	1,0	1,0	0,5	2.4

After combustion of woody fuels most elements taken up by the tree will remain in the ash with exception of nitrogen and sulphur. The carbon content in the ash depends on the combustion technique used. The amount and composition of wood ash depends on tree species and compartment, whereby zones of high growth rate, such as the bark, branches, tips and leaves and needles show a higher concentration of inorganic elements (Tables 7-8). When using wood as a fuel, soil particles usually enter the furnace together with the fuel which will add quartz and feldspars to the mineral matter.

Ash characteristics will also depend on the type of combustion process used. Due to the lower combustion temperature in a FBC boiler, bottom ash and bed material are mainly crystalline. Further, quartz sand is often used as bed material leading to a Si-content in the ashes which is generally higher than in other types of ashes (Steenari, 1998).

Wood ash contains many reactive and strongly alkaline components which make some kind of stabilisation necessary before using it as a fertiliser. This can be carried out by moistening and agglomeration of the ash (well-burnt ash can agglomerate spontaneously). This process is important because it reduces the solubility of certain elements in the ash and avoids a pH-shock to the soil and burning damages on plants (Steenari, 1998).

3.5.1.4 *Straw and peat ash*

Peat consists of partly decomposed biomass. The chemical composition of the peat depends on several factors as type of soil and rock at the location and how the water enters the peat bog (precipitation, run off from surrounding soils). Peat bogs with a high content of metals are usually not used for energy production. When using peat (and coal) as a fuel, lime is often added to reduce the sulphur discharge.

Peat ash mainly consists of three different components: a) nutrients and trace metals from the biomass; b) secondary precipitates as calcium carbonates and iron carbonates, -phosphates, -hydroxides, gypsum and sulphides: c) quartz and feldspars from the adhering soil (Tammela *et al.*, 1997). The ash content in peat varies between 5 and 15 %.

According to Hedvall (1997) the ash content for straw is 4-5 % of the dry matter.

3.5.2 Fate of radiocaesium during conversion

3.5.2.1 *Fate of radiocaesium during combustion*

The behaviour of caesium in an open fire have been investigated by Amiro *et al.* (1996). Biofuels studied were straw, peat, pine and aspen. The biomass was sprayed with $CsNO_3$. Samples of flue gases and ash were collected during and after combustion. It was found that for temperatures common for field fires, the loss of caesium to the atmosphere was 40-70 % of the total caesium content while at higher temperature (1000° C) almost all caesium was evaporated.

The percentage of radiocaesium in the fuel that can be found in the ashes depends on the type of power plant and the characteristics of the biofuel. Jantunen *et al.* (1992) examined the behaviour of Chernobyl fallout nuclides during peat combustion at four different heating plants in Finland where different combustion techniques have been used. An increased enrichment factor for smaller ash particles was found, which indicates that the radiocaesium evaporates in the furnace and condenses on the fly ash particles when the flue gases cool in the heat recovery sections of the boiler. As the surface to volume ratio of a particle is inversely proportional to its diameter, the smallest particles collect the highest amount of caesium. For peat the average enrichment factor was 15 for fly ash and 10 for bottom ash. For wood, Hedvall (1997) found an average enrichment factor for radiocaesium of 41 for fly ash and 26 for bottom ash.

Hedvall (1997) examined the activity balance for in- and outgoing radioactivity in a peat fired heating plant using cyclones and textile filter. The result showed that 12 ± 2 % of the radiocaesium escaped through the stack. Eriksson (1998) estimated the fraction of the radiocaesium that disappears with flue gases and condensation water in a modern wood fired heating plant equipped with modern filters and heat recovering system, at 1 %. This means that 99 % of the radiocaesium content in the fuel can be found in the ash or on surfaces in the combustion system. This is in accordance with data from a Finnish peat fired power plant where 0.4 % of the in-going radiocaesium could be found in the discharge (Nordliner, 1989).

3.5.2.2 *Fate of radiocaesium and strontium during gasification*

In collaboration with UCL-TERM (Biomass Energy Group) the fate of radiocaesium and radiostrontium was studied in a 100 kWt benchmark downdraft fixed bed gasifier. The facility includes gasifier, cyclone, water scrubber for gas cleaning and impingement filter for gas sampling. The specifications of the gasifier are given in Table 9. The temperature in the reaction zone is between 700-900 °C and the temperature of the gas produced is 400 °C.

Table 9: Specifications of the UCL-proto-type downdraft gasifier

Design Parameter	Specification
Fuel feed-rate (maximum)	35 kg h^{-1}
Thermal input (maximum)	180 kW
Gasification agents	Atmospheric air
Air flow-rate	40 Nm³ h^{-1}
Product gas flow rate	65 Nm³ h^{-1}
Product gas temperature	400 °C
Product gas LHV	5-6 MJ Nm^{-3}

The feedstock consisted of chips from 3-year-old willow wood with moisture content of 12 %. To simulate a wood contamination by ^{137}Cs and ^{90}Sr respectively, the chipped biomass was sprayed with water containing stabl Cs and Sr (Cl$^-$-form). In order to calculate mineralomass distributions and balances, element content (Ca, Fe, Si, Al, Fe, Ca, Mg, K, Na, Zn, Mn and Cs and Sr) was measured in the fuel, the residual bed material (gasifier reactor), ash products (bottom ash from the ash-pot and fly ash from the cyclone) and the liquid (water scrubber) and the gaseous effluents.

Ca and K were the dominating components of the ashes of the willow chips and levels are comparable with those found for other wood fuels (Figure 13 and Table 10). The residual particles were rather recovered in ashes than in tar. Fine particles removed with liquid and gaseous effluents constituted about 8 %.

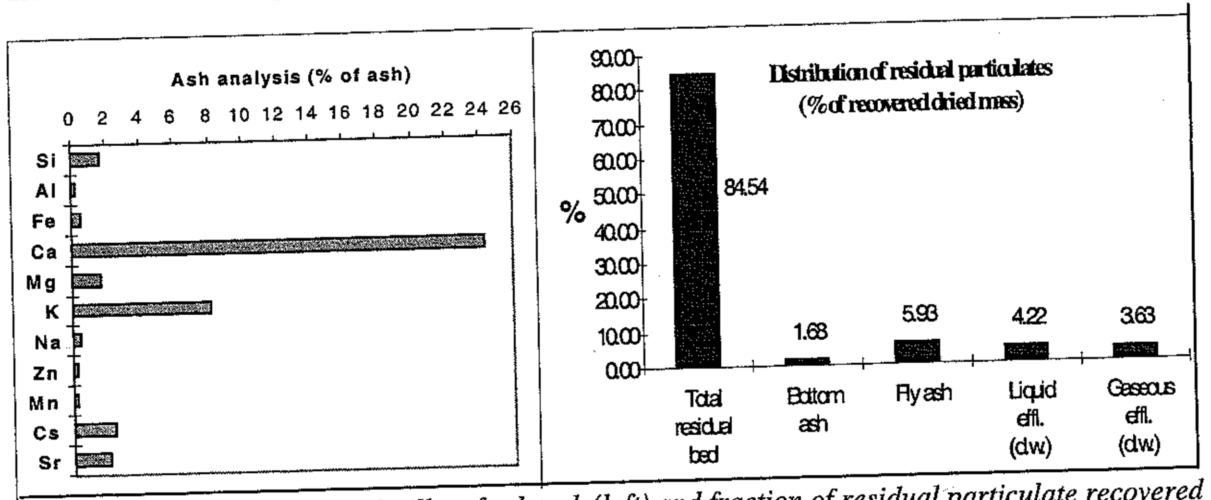


Figure 13: Ash composition of willow feedstock (left) and fraction of residual particulate recovered in different compartments of a gasification unit (right)

Most elements showed a distribution between compartments comparable to the mass distribution of the residual particles. Generally recoveries between 92 and 99 % were obtained. Sr (and Ca, Mg, Mn) showed the lowest mobilisation as illustrated by the highest content in residual ashes (> 99.7 %) and less than 0.01 % in the gaseous effluents. Cs and K were the most mobile among the elements studied with 2.4-5.7 % in the gaseous effluent. The enrichment factors (calculated as the ratio of element concentration in recovered material and that in willow chips) on particles of different size classes are presented in Table 10.

The residual bed material consisted predominantly (55 %) of large particles (> 2 mm). Fine particles (<0.2 only contributing for 13 %. Further, Si, Al, Fe, Ca, Mg and Sr were mainly concentrated on medium size parti and secondly on fine particles. K, Na, Zn, Mn and Cs accumulated predominantly on fine particles, more tha medium and large particles.

Table 10: Enrichment factors in the residual char bed for different particle size classes

Particle size range	Particle mass distribution (% dw)	Element										
		Si	Al	Fe	Ca	Mg	K	Na	Zn	Mn	Cs	Sr
<0.2 mm	13	48	51	239	35	44	21	31	22	80	16	40
0.2-2 mm	32	72	71	279	42	56	16	22	6	75	10	43
> 2 mm	55	14	14	90	11	12	11	14	3	18	20	9

About 6 % of the Cs escaped from the installation while only 0.007 % of Sr was released with gaseous effluents. This is partly due to Cs condensation on the finest particles which are transported with the gas stream. According to a permissible level of 40 Bq ^{137}Cs m^{-3} in gaseous effluents, and assuming a routine release associated with operational conditions of present pilot system, it was calculated that the maximal ^{137}Cs content in wood suitable for gasification would be 1240 Bq kg^{-1}. This is higher than the exemption level of 740 Bq kg^{-1} set for fuel wood in Belarus.

3.5.2.3 Associative properties of ^{137}Cs in biofuel ash.

The availability of radiocaesium in the ashes is important on two accounts: 1) the risk of radionuclide leaching when ashes are disposed off and 2) the risk of transfer to the biomass and leaching when applied as fertiliser.

The chemical form of radiocaesium in wood fuel ashes has been studied by sequential extraction of ashes from two Swedish heating plants with grate fired burners (Ravila, 1998). At one heating plant most radiocaesium (70-80 %) was found in the water soluble fraction and the fraction available by ion exchange. The water soluble fraction of the bottom ash (20 %) was much lower than the water available fraction of the fly ash (40 %). The ash from the other heating plant contained a larger fraction of unburned fuel. The water soluble part of the radiocaesium for this plant was much lower, 4 % for the fly ash and 8 % for the bottom ash. The total biological available fraction was 60 % for the fly ash and 30 % for the bottom ash.
The biologically available fraction of caesium in peat ashes varied between 0 and 10 % for bottom ash and between about 10 and 50 % for fly ash. This low availability may be attributed to the high concentration of iron and silica and the fact that iron oxides may act as a catalyst for the alkali metal association to silica particles.

Ravila (1998) has also compared the concentration of radiocaesium in wood for a forest fertilised with wood ash with an untreated forest. The deposition in the area was 1600 - 2500 Bq m^{-2} and was located in the organic layer. Wood ash in a granulated form from a district heating plant of Central Sweden was distributed at a rate of 4000 kg ha^{-1}. The ^{137}Cs concentration in the ash was 2.2 Bq g^{-1} resulting in an average deposition of 900 Bq m^{-2} of which about 25-50 % still remained within the granulates 5 years after the distribution in the forest. The ^{137}Cs activity in the stem wood from the wood ash treated area (15 Bq kg^{-1}) was twice as high as for the untreated area. ^{137}Cs distribution between annual rings showed that the concentration of ^{137}Cs was highest in the youngest wood. Rantavaara (personal communication) said that preliminary results from plots fertilised with Cs-containing ashes showed that Cs-uptake decreased. The observation was explained by the high amounts of K also added with the fertiliser.

3.5.2.4 Valorisation of wood in a pulp and paper plant

Stem wood may also be used as raw material in the production of paper pulp. The main purpose of the pulping process is to extract the cellulose fibres from the wood. The fibre yield is much higher for the mechanical pulps (~100 % yield) than for the chemical pulps (40-70 %).
In mechanical or ground-wood pulping the wood is torn into pulp by pressing the wood against an abrasive rotating grinding stone. The water used in the process is recycled after purification and than used in the paper machine. Ground-wood pulps can be expected to retain a large fraction of the radionuclides present in the wood before pulping. The fraction of radionuclides that dissolve into the process water are largely removed during the water purification stages.
In the chemical pulp processes wood is cooked in a digesting agent, either acid alkaline or neutral which acts to soften the wood structure. At the end of the cooking the mixture of softened wood chips and spent digesting agents are directed to a washing plant where fibres are separated from the black liquor containing the digesting agents. Black liquor is directed into an evaporation plant in order to remove excess water and is then fed into the recovery boiler for combustion. The bark is burnt in the same combustion unit (Ravila, 1998).
For a typical alkaline pulp plant the inputs, outputs and radiocaesium concentration factors are given in Table 11 (Ravila, 1998)

Table 11: Inputs, outputs and radiocaesium concentration factors for an alkaline pulp plant (Ravila, 1998)

Input		Output		
Product	*Amount*	*Product*	*Amount*	*Conc. factor*
Dry wood	2.4 t	Bark Ash	0.01 m³	68
Water	92 m³	Black liquor	0.05 m³	26
Chlorine, NaOH, O_2, H_2O_2	0.074 t	Lime sludge	0.03 m³	Not sign.
H_2SO_4	0.026 m³	Na_2SO_4	0.0024 t	195

3.5.2.5 *Conclusions for wood biofuel*

From the information above it can be concluded that the main part of the radiocaesium can be found in the ash in a modern biofuel fired heating plant. The enrichment factor is generally higher for fly ash than for bottom ash. Mainly fly ash is produced but the ratio of produced fly ash/ produced bottom ash has a large variation. With an appropriate filtering system, more than 99 % of the fly ash can be separated from the flue gases. The separation of radiocaesium can be a few percent lower due to higher enrichment of radiocaesium and lower collection efficiency for smaller ash particles. For the pilot gasification plant, Cs recoveries were about 95%.

There is not sufficient information available to closely describe advantages and drawbacks for different combustion techniques from a radiological point of view.
For biofuel ashes two options seem realistic, to treat it as waste and dispose it in a landfill or use it as fertilisers. The use of biofuel ash in construction material is not recommended given the high level of alkali metal species and chlorides. A large part of the radiocaesium in wood ash can be mobilised. From sequential extraction experiments it has been shown that between 70-80 % of the radiocaesium can be biologically available for certain ashes, where the water soluble part was between 5 and 40 % for the different ashes. In peat ash the extractable fraction of radiocaesium is lower than for wood ash.
When using ash as a fertiliser some kind of pre-treatment as granulation or agglomeration is necessary to avoid damaging the plants and the soil. One should also bear in mind that the use of ash as a fertiliser may be restricted by the presence of hazardous elements like heavy metals.

3.5.2.6 *Other biofuels*

Although information is available on soil-to-plant transfer factors for radiocaesium for the bioenergy crops of interest, only limited information is available on the fate of radionuclides during the biofuel production process. In Gopa (1996) information could be found on the TF to rape seed, rape seed oil and cake. The TFs to ethanol from winter wheat and to sugar for sugar beet (0.5 kg ethanol formed per kg sugar) were calculated with the same ratio between the TF between rape seed and rape seed oil. The remaining activity was assumed to go entirely to the side product(s) and the TFs were calculated considering the weight of the side product formed. (Goor, 1998a) compared the amount of seed, root and energy product. In Table 12 mean TFs for the different cultures considered are given together with the activity levels for different surface contaminations. These activities can be compared with the limits for ^{137}Cs for food consumption (grain, oil, ethanol, sugar) and fodder use or burning (wood straw) in Belarus (Gopa, 1996) presented in Table 13. No information was found on TF to other by-products as e.g. glycerine.

It is clear from Table 12 that the contamination levels in the primary fuels for the different routes are of no concern. Assuming the high TFs for coppice in Belarus apply, use of wood for combustion in household wood stoves should be considered with care. It should, however, be noted that, except for the TFs to rape seed and rape seed products, the TFs recorded are mean values for European conditions where soils are well fertilised. The TFs obtained for Belarus were recorded on very poor soils, which were, moreover, out of production for more than 10 years when the coppice trials were established. Their K-status was very low and it is known that at low K Cs-TF increases exponentially (Smolders *et al.*, 1997, Nisbet *et al.*, 1999). The mean TF for Sweden of 10^{-5} m² kBq^{-1} and of 5 10^{-5} m² kBq^{-1} recorded for the Belgian sandy soil, are probably more realistic figures for European soil conditions.

Table 12: TFs to food crops and products (10^3 m² kg^{-1}) and contamination levels, amount of waste and amount of waste per net energy output for 3 contamination scenario (185, 555 and 1480 kBq m^{-2}, 5-15-40 Ci km^{-2})

CROP§	**TF**∞	**Contamination level Bq kg^{-1}**			**Waste produced kg ha$^{-1,*}$**			**Amount**$ **kg ha^{-1}**	**Energy**§ **MJ ha^{-1}**	**kg Waste per GJ**#		
		185	555	1480	185	555	1480			185	555	1480
RAPE SEED					240	240	1940		**Input** 53589	2.4	2.4	26.8
Seed	0.45	83	250	*666*				3000				
Straw	0.63	117	350	*932*				6000	82836			
RME$^+$/oil	0.11	20	61	163				1120	44850			
Oil cake	0.86	159	477	**1273**				1700	26480			
Straw ash (4%)	30	5550	16650	44400				240				
Cs in exhaust$^\nabla$		1.16	3.47	9.25								
WHEAT					184	184	184		**Input** 53589	1.8	1.8	1.8
Grain	0.06	11	33	89				5100				
Straw	0.30	55	166	444				4600	94162			
Ethanol	0.01	2.8	8.3	22				1460	57486			
Rape	0.13	24	72	193				184	3003			
Straw ash (4 %)	7.5	1110	4163	11000				2180				
Cs in exhaust$^\nabla$		0.16	0.47	1.26								
SUGAR BEET							4000		**Input** 130296			95.8
Roots	0.43	80	239	636				13000				
Leaves & tops	0.6	111	333	888				3000	60235			
Sugar	0.06	10	31	81				9000				
Pulp & vines	1.27	236	707	**1885**				4000	117213			
Ethanol	0.11	20	61	163				4500	111825			
Cs in exhaust$^\nabla$		0.58	1.73	4.63								
COPPICE									**Input** 10583			
Wood, Sweden	0.01	1.9	5.6	15				12000	220800			
Ash (2%)	0.5	92	277	740				240				
Cs in exhaust$^\nabla$		0.06	0.18	0.48								
COPPICE						240	240			1.1	1.1	1.1
Wood, Belarus	2	370	1110	2960				12000				
Ash (2%)	100	18500	55500	14800				240				
Cs in exhaust$^\nabla$		11.2	35.7	95								
FORESTS										1.1	1.1	1.1
Wood	2	370	1110	2960				6000				
Ash	100	18500	55500	14800				120				
Cs in exhaust$^\nabla$		11.2	35.7	95								

§: Type and amount of components and their energy content according to Goor, 1998a. The energy input for the system is given in bold.
$: Ash content of wood and straw after combustion for energy recuperation according to Hedvall, 1997.
∇: Cs in exhaust for rape seed during burning of RME in diesel motor considering 17.6 m³ gases are produced per kg RME. A similar conversion was used for the combustion of ethanol. For the gasification of wood the data from the gasification unit were used: with a measured dust loading of 0.87 g m^{-3} and a dust/wood concentration factor of 37.
∞: Rape seed: values according to BRISSA (Table 5-19 in GOPA, 1996); Wheat: most probable value on sand according to Nisbet *et al*, 1999; Sugar beet: Roots: IAEA, 1994; leaves and tops: most probable value for green vegetables for sand following Nisbet *et al.*, 1999; Coppice: mean value for Belarus on sand and most probable value from Swedish trial
*: A component is only considered as waste if the specific limits presented in Table 13 are exceeded. Ash is only considered as waste if the ^{137}Cs concentration is higher than 1000 Bq kg^{-1}, the lowest limit for LLW.
#: If a component is considered as waste, its energy content is not considered. The amount of waste per net amount of energy produced is calculated from the ratio kg waste and the difference between energy output and input.
+: RME Rape Methyl Ester

When the mean TF recorded in the Swedish trials would prevail, there would be no problem for burning the coppice wood. To the contrary, with the TFs to wood for coppice on the peaty soil in Belarus, similar as the TFs in forests, limits for wood fuel are exceeded when surface contamination is 370 kBq m^{-2} or higher. A comment on the exemption level of 740 Bq kg^{-1} for fire wood is to the order. The level of 740 Bq kg^{-1} for fire wood is also for use in household wood stoves. For combustion at industrial scale with adequate filtering followed by appropriate ash-handling limits for fuelwood levels may be considerably higher. The maximal level for incineration of agricultural waste products is 3.7 MBq kg^{-1} (see section 3.6, Grebenkov, personal communication).

The secondary products as oil cake, rape, pulps and vines leaves and beet tops, may be used for fodder consumption. Also straw may be used as fodder. For wheat, products may be safely used as fodder. Only at the highest contamination level, straw should not be used for dairy cows yet can be used for meat production. At the highest deposition level considered, rape seed straw should not be used as fodder for dairy cows. At 555 kBq m^{-2} oil cake can still be used for meat production. At 1480 kBq m^{-2} the contamination level of the oil cake exceeds the limit for any fodder use and should hence be discarded as waste. The same can be said for the pulp and vines from the sugar beet pathway.

The rape seed and wheat straw can also be burnt. Given the low TF to wheat straw burning, this type of straw is of no concern for the contamination situations considered. Concentration in rape seed straw may exceed the 740 Bq kg^{-1} limit for use as fuel. At depositions of about 800 kBq m^{-2} or higher, paradoxically, the straw can still be used as fodder for meat production.

Cs-levels in the exhaust gas following fuel conversion to electricity or heat is below the acceptable limits for the public for all cultivation and conversion systems considered. Exhaust from gasification of coppice cultivated in Sweden is a factor 3 (sugar beet) to 20 (oil seed rape) lower than for the other crops. It should be emphasised that the calculations for the Cs emissions from the pilot gasification unit are conservative in that not the optimal filtering system was used. With the coppice TFs recorded in Belarus, permissible levels for the public are exceeded when willows are cultivate in areas with contamination levels exceeding 620 kBq m^{-2}. Dose limits for workers are not exceeded. The values mentioned in Table 13 are, moreover, conservative since the exhaust emissions are always mixing with the surrounding air. This assumption is corroborated with the few µSv dose contribution from atmospheric release of contaminated fly ash from wood with 1000 Bq kg^{-1} ^{137}Cs. For comparison: the specific activity in the air generated by re-suspension processes from soil with 740 kBq m^{-2} ^{137}Cs ranges between 0.7 and 7 Bq m^{-3} (GSF, 1993).

Table 13: Belarus activity limits for ^{137}Cs in some food products, cattle feed and wood (Bq kg^{-1}) (GOPA, 1996) and for gaseous effluents (Belgian KB, 1963 Art. 36)

Product	**Limit**	
Food consumption		
Oil and fats	185	
Bread, Flour, Sugar	370	
Fodder	*Milk production*	*Meat production*
Hay	1480	1850
Straw	370	1110
Hay Forage	740	1110
Silo	296	555
Vegetable root crop	370	370
Grain	370	592
Green mass	185	296
Wood, straw for burning	740	
Gaseous effluents	40 Bq m^{-3} (public) 2000 Bq m^{-3} (workers)	

3.6 Waste

Decontamination and remediation activity in the territories contaminated after Chernobyl accident has resulted in a large volume of radioactive materials in the CIS which show activity levels below than Low Level Waste (LLW, 1 Bq g^{-1} to 100 Bq g^{-1}). This type of waste has been included in regulations as so called "Conventionally Radioactive Waste" (CRW) requiring control and special management. Nearly all bulk of ash from contaminated biomass-fired facilities is supposed to belong to CRW and the lowest range of LLW. The State Standard of the Russian Federation, No GOST(R) 22.8.02-94 called Disposal (Dumping - in original) mentions that radioactive waste of agriculture (contaminated agricultural products and by-products which level of radioactive contamination exceeds the permissible limits) are to be utilised or disposed off. The utilisation of radioactive agricultural waste is accomplished to produce economic value (heat, power) or secondary valuable products (cellulose, pulp, chemicals, etc.) other than food. Only appropriate technologies approved in accordance with certain procedure must be used. Otherwise these waste must be disposed off. Incineration is considered as the appropriate technology to convert the combustible agricultural waste (crops, straw, grass, woody waste, etc.) into ashes. Incineration is applied if specific activity of an initial waste form does not exceed 3.7 MBq kg^{-1}. This is higher than the acceptable level for fuel wood but also IAEA (1992) mentions that when a large area is contaminated, as is the case after a nuclear accident, nuclear waste handling may have to be performed outside the IAEA regulations.

The ashes should be confined to prevent resuspension and be disposed off outside any settlement border. The characteristics of the waste repository proposed for Belarus are rather simple. A trench of 3-5 m deep and 6-12 m width lined with 0.5 m-layer with an infiltration coefficient < 10^{-5} cm s^{-1}. The exposure dose rate in distance of 1 m from the surface of the ground cover must not exceed 28 µSv h^{-1}. The expected cost are 8 Euro m^{-3} waste (Grebenkov, personal communications).

Since biomass containing up to 3.7 MBq kg^{-1} may be incinerated under specified controlled conditions, and considering the coppice TF for Belarus (2 10^{-3} m² kg^{-1}), this would imply that coppice can be cultivated in areas contaminated up to 1850 MBq m^{-2}. In such a scenario, cultivation would be banned on grounds of exceedingly high external exposure (> 1 Sv a^{-1}). The discussion on waste in continued in chapter 7.

3.7 Conclusions

On radio-ecological grounds there is not much concern for any of the cultures. Activity levels in the useable plant parts are generally low and the same holds for the by-products. Only when cultivated on very contaminated land (1000 kBq m^{-2}) some by-products should be treated as waste.

Estimates on radiocaesium concentration in the wood were not yet adequate. K seems to play an important role but cannot explain differences between TFs obtained for willows in different regions. Soil parent material [clay mineralogy and hence radiocaesium adsorption and fixation potential (ageing)] may play an important role. In K-poor soils, fertilisation may decrease the radiocaesium TF considerably.

TFs for willow wood were generally smaller than for common forests, in place at the time of the accident. Since also biomass production in a SRC is higher (if water supply and soil fertility is adequate), and revenue faster and more regular, willow SRC seems a valuable alternative compared to forests.

Considering the exemption limit for radiocaesium in fuel wood (740 Bq kg^{-1}) only regions with rather low radiocaesium deposition can be considered for SRC cultivation (< 370 kBq m^{-2}) if soils are poor in clay and low in K. However, as materials with contamination levels up to 3.7 MBq kg-1 may be burned in controlled electricity or heat plants, willow SRC cultivation may be advised in regions with much higher contamination levels. Adequate exhaust filtering systems should be installed in these circumstances and appropriate disposal of the ashes should follow. In case the soil-to-wood TFs apply for soil with a high RIP and sufficient K-status, levels in the wood will always be below the exemption limit for fuel wood (except if deposition exceeds 100000 kBq m^{-2}).

4 Radiological aspects of SRC production and conversion

4.1 *Introduction*

Producing coppice fuel wood on contaminated land may lead to enhanced radiation doses to workers involved in production and conversion. Establishing, maintaining and harvesting the crop results in external exposure from radiocaesium deposited on the ground. Further there is the exposure during transport of the fuel to the combustion site.

Workers may be exposed at the power plant. Wood-firing of ^{137}Cs contaminated fuel causes an enrichment of ^{137}Cs in the produced ash. The concentration of ^{137}Cs in the ash is usually between 40 – 80 higher than in the wood fuel. This makes deposits, containers and other locations, where ash is accumulated, critical sites from a radiological point of view. Following is a summary of dose calculations for different situations relevant for production of energy from contaminated willow. No information was found to make dose calculations for the liquid-biofuel conversion.

4.2 *External effective doses at a radiocaesium contaminated cultivation field*

One of the most crucial parameters from a radiological point of view is the time spent at a contaminated area. In SRC production, time is spent at the field for establishment, management and harvesting. A high mechanisation level will result in higher working efficiency and better shielding, both entailing lower doses.

4.2.1 Calculation method

In the calculation the ploughed cultivation field has been modelled as an infinite slab source with different depths. The composition of the soil was set to: Si (8.2 %), Al (3.17 %), Ca (25.1 %), Fe (2.33 %), K (0.87 %), Mg (3.08 %), P (1.01 %), S (2.1 %), O (52 %), C (2.14 %) and the apparent soil density to 1500 kg·m^{-3}. The methods that have been used for the calculations are described in Finck (1992). For the plane source the dose rate conversion coefficients were taken from Kocher (1983). Dose rate factors for ^{137}Cs and ^{134}Cs are given in Table 14. In a short-term perspective after an accident like Chernobyl, ^{134}Cs can contribute considerably to the external effective dose.

Table 14. Dose rate factors [μSv·h^{-1} per Bq·m^{-2}] *for* ^{137}*Cs and* ^{134}*Cs.*

Ploughing depth [m]	**0**	**0.1**	**0.2**	**0.25**
^{137}Cs	$1.9\cdot10^{-6}$	$7.7\cdot10^{-7}$	$4.3\cdot10^{-7}$	$7.7\cdot10^{-7}$
^{134}Cs	$4.9\cdot10^{-6}$		$9.0\cdot10^{-7}$	

4.2.2 External doses at ploughed and un-ploughed fields

For an uniformly distributed slab source (depth 0.25 m) with a contamination level of 1480 kBq·m^{-2} the effective dose rate is 0.52 μSv h^{-1} (Table 15). This means that 2000 hours can be spent on an area with this contamination before receiving an external effective dose of 1 mSv. Newly deposited ^{137}Cs from fallout approximated with a plane source gives an effective dose rate of 2.9 μSv h^{-1} which means that approximately 345 hours exposure leads to the effective dose of 1 mSv.

Table 15: External dose rate (μSv h^{-1}) from ^{137}*Cs deposition for undisturbed and disturbed (10-25 cm) plane source*

Deposition [kBq·m^{-2}]	**37**	**185**	**555**	**1480**
Infinite plane source	0,07	0,36	1,1	2,9
10 cm thick slab source	0,03	0,14	0,43	1,15
25 cm thick slab source	0,01	0,06	0,19	0,52

This shows the importance of mixing the soil after the fallout has occurred in order to reduce the photon fluence rate. Converting a plane surface source to a uniform slab source by ploughing reduces the effective dose by a factor 5. Comparable reductions following ploughing (factor 1.9-5.9) were also found when calculating the external dose rate for the virgin and ploughed soils at the Belarus test sites from the radiocaesium distribution in the profile at both locations (Monte Carlo Model, MCNP version, considering shine from distances up to 16 m) (Vandenhove *et al.*, 1999). For mechanised plantation, fertilisation and harvesting, the effective dose will be further reduced due to the shielding effect of the vehicles involved.

4.3 *Comparison of dose during coppice and oil seed rape production*

Since the external dose from ground shine is the major pathway contributing to the dose the time spent on the field during production is an important parameter. Coppice is not a labour intensive culture compared with normal agricultural cultivation system. As an example external dose rates are compared for coppice and oil seed rape production. A total coppice cycle (24 years) is considered. Data presented are for a Western European scenario and are extracted from the data sheets for the economic modelling (Chapter 7).

Coppice

Establishment of culture: 1st year: 2 h ha^{-1}
Maintenance: 2 out of 3 years: 0,4 h ha^{-1}; over 24 years 0.4*16=6.4 h ha^{-1}
Harvesting: each 3rd year: 2 h ha^{-1}; over 24 years 2*8= 16 h ha^{-1}
Final grubbing up: last year: 3 h ha^{-1}
Total time spent over 24 years: 27.4 *h ha^{-1} or 1.14 h ha^{-1} a^{-1}*

Oil rape seed

Establishment, maintenance and harvesting: every year: *3,9 h ha^{-1} a^{-1}*

For a deposition level of 1480 kBq m^{-2} and without ploughing this would result in a yearly dose of 3.3 μSv ha^{-1} for coppice and 11.3 μSv ha^{-1} for rape seed. For a ploughing depth of 25 cm the exposure would be reduced with a factor 5. In the dose calculations, no shielding from machinery is considered. In case less adapted planting (e.g. machine for planting vegetables: 5 h ha^{-1}) or harvesting machinery (e.g. silage harvester: 4 h ha^{-1}) are used as may be the case in Belarus, the average annual dose over the whole culture period would mount to 3.8 μSv ha^{-1} for a surface deposition of 1480 kBq m^{-2}. In case all planting and harvesting would be done manually, this would require 40 and 115 h ha^{-1}, respectively, and the corresponding doses in the year of planting and harvesting would be 116 and 333.5 μSv ha^{-1}. Under those extreme conditions, a farmer should not plant more than 8 ha a^{-1} or harvest more than 5 ha a^{-1}. The dose rates given are for a plane source and are hence very conservative since for establishing a coppice field the soil has to be at least disked over a depth of 15 cm.
Dose contribution from standing wood is also negligible.

For comparison, the annual dose received from the consumption of potatoes grown on a sandy soil with deposition of 1480 kBq m^{-2} (0.5 kg d^{-1} and 66 % of the ^{137}Cs left after preparation) is 246 μSv.

4.4 *Dose during transport*

Estimations of doses from transportation of contaminated wood (photon fluence following Kase and Nelson (1977), 1.5 m from source with 1.3 m radius, 500 kg, s.g. 700 kg m^{-3}) cultivated on a field of 1480 kBq m^{-2} and a TF of 2.5 10^{-3} m^2 kg^{-1}, showed that this dose pathway is negligible (~0.2 μSv ha^{-1} a^{-1}) compared to external radiation dose from ground shine.

4.5 *Doses to workers at a power plant firing* ^{137}*Cs contaminated wood fuel*

The calculations were based on the conceptual design of the operating Måbjerg plant (I/S Vestkraft and Elsaproekt A/S, 1994) in northern Jutland, Denmark, where the fuel is partially constituted by 25 000 t of wood chips annually. The boiler of this plant is a combined unit, which can be fired with either straw, wood chips or any combination of the two materials. The dose calculations presented focus entirely on wood chip firing.

4.5.1 Calculation method

Dose rates were calculated using the Monte Carlo model MCNP (Briesmesiter 1993). The statistical uncertainties of the calculated results were in all cases less than 5 %. All major statistical checks were done.

4.5.1.1 *Fuel contamination level*

Considering the TF obtained at the Belarus trials of 2 10^{-3} m² kg^{-1} and a deposition of 1480 kBq m^{-2} the resulting specific ^{137}Cs content in the willow wood would be 3000 Bq kg^{-1}. With the average soil to wood TF obtained for the Swedish and Belgian trials (10^{-5} m² kg^{-1}) the ^{137}Cs contamination level would only be 60 Bq kg^{-1}. Bottom ash is generally assumed to have a density of 800 kg m^{-3}, whereas fly ash is assumed to have a density of 400 kg m^{-3} (Jensen and Jorgensen, 1998). These figures were used in all calculations.

4.5.1.2 *Contamination geometry's*

After consultation with power plant engineering experts (Jensen and Jorgensen, 1998) who worked out drawings showing the geometry's of the Måbjerg power plant 6 categories of locations of significant concentrations of bio-material ash were identified. The doses have generally been calculated for two distances (0.5 m and 5 m) from these locations.

Bottom-ash on sides and bottom of the boiler

Bottom-ash may build up on the inside walls and bottom of the boiler. Only the parts of the boiler that might influence the dose rate from the contamination in this bottom-ash were modelled. Therefore, the design was simplified, and the boiler was modelled as a box with a height of 17.15 metres, and side-lengths of 14.25 metres and 6.70 metres. The boiler sides were modelled as 200 mm thick Rockwool (the density was estimated to be 160 kg m^{-3}) covered by 2 mm thick aluminium sheet. On average, the inside walls of the boiler are assumed to be covered with a 5-10 mm thick layer of bottom-ash. In this case, the highest of these values was applied to make the dose rate calculations conservative. The bottom of the boiler was assumed to have a thicker coating of about 25 mm of bottom-ash.

Fly ash in bag house

Flue gas from the boiler is led through a bag-filter, which is at the power plant in Jutland designed for a maximal flue gas production rate of about 70 000 Nm³ h^{-1}, so that the dust content is reduced to typically about 10 mg per Nm³. Filtered flue gas is then normally released through a 120 m high chimney at ca. 105 °C.

The bag house building was modelled as having 5-mm thick steel walls. The building is assumed to be divided in four chambers. In each chamber, with dimensions of 3.5 m by 3.5 m (side-lengths) by 6 m (height), there would be a total of 240 thin membrane filter bags. Each bag has a length of 6 m and a diameter of 12.7 cm. On average, it is assumed that the bags are coated with a 0.75 cm thick layer of fly-ash. The corresponding volume of fly-ash in total in the four chambers would be 17.2 m³.

If this volume of fly-ash were expanded over the whole chamber volume, the corresponding density would be 23.5 kg m^{-3} (excluding the small contribution of the empty bags). Since the chamber has very large dimensions, the distance from the chamber to a person is not an extremely critical parameter in the evaluation of doses received. Based on a drawing of the Måbjerg plant, this distance is assumed to be about 6 metres on average, when a person is standing in the bag house, directly under the chambers. In reality, this would only be possible during repairs or maintenance.

Fly ash in fly-ash silo

The fly-ash from the bag house filter is led to a fly-ash silo. Based on the power plant drawings, the fly-ash silo was modelled as a cylindrical container with a diameter of 2.8 m and a height of 6 m. In the model the walls of the fly-ash silo consist of steel of 5 mm in thickness. The fly-ash silo was assumed to be filled half with fly-ash. The ^{137}Cs concentration in the fly-ash was again assumed to be 80 Bq cm^{-3}.

Two 'big bags' filled with fly ash

From the fly-ash silo the ash is discharged to plastic 'big bags'. Two filled 'big bags', each containing a volume of 1.7 m³ of fly ash (modelled with a height ca. 1.7 m and side-lengths ca. 1 m), can be assumed to be more or less permanently located in the close vicinity of the fly-ash silo. Filled 'big bags' will eventually be replaced and transported to a well-shielded repository in the vicinity of the power plant

Bottom ash conveyors

The ash from the bottom of the boiler is transported to a bottom-ash container. This transport occurs through bottom-ash conveyors, which may have different designs. Calculations were made of the doses received from standing close to a bottom-ash conveyor. Based on drawings of the Måbjerg plant, one type of conveyor is assumed to have a cross-sectional height and width of 90 cm and 55 cm, respectively. Its length is assumed to be 8 m. The walls are assumed to have been made of 5 mm thick steel. It is assumed that the three sides of the conveyor will be covered with a 5 cm thick layer of bottom-ash.

In a spiral type conveyor the bottom-ash is pushed through with a rotating screw. With this cylindrical type of conveyor, it is generally so that maximally 40 % of the space is filled with bottom-ash, and this is what was assumed.

Bottom ash in two containers

At the Måbjerg plant there are two bottom-ash containers connected to the conveyors. These both have the cross-sectional dimensions of 1.6 m by 1.2 m and a length of 4.8 m. They are assumed to have 5 mm thick steel walls and to be half-full of bottom-ash, on average.

4.5.2 External exposure

Table 16: Calculated dose rates in units of nSv·h^{-1} per Bq·cm^{-3} in the ash,

	Boiler	Bag house	Fly-ash silo	'Big bags'	Bottom-ash conveyor	Spiral bottom-ash conveyor	Bottom-ash containers
D = 0.5 m	3.15	3.62*	68.5	56.2	3.2	1.9	29.3
D = 5 m	1.43		14.5	1.41	0.063	0.03	2.1

* Dose rate to people standing directly under the bag house filter.

Table 17: Calculated annual doses (mSv a^{-1}), received by workers (2000 h) at a power plant firing willow wood with 3000 Bq kg^{-1} ^{137}Cs

	Boiler	Bag house	Fly-ash silo	'Big bags'	Bottom-ash conveyor	Spiral bottom-ash conveyor	Bottom-ash containers
D = 0.5 m	1.5	0.9*	16.4	13.5	1.6	0.9	14.1
D = 5 m	0.7		3.5	0.4	0.03	0.02	1.0

* Doses to people standing directly under the bag house filter.

4.5.3 Inhalation risks

If repairs and/or maintenance demand access to the closed ash containers, or significant concentrations of contaminated ash or dust are somehow suspended into open air at the power plant, it would be recommendable that operators wear masks to protect against inhalation of radioactive material. However, under normal operation of the power plant, the following recommendation of the ICRP (1997) should certainly be addressed: "The use of personal respiratory protection is likely to reduce the general working efficiency and hence result in longer work times to complete tasks. The resulting increase in external radiation exposure and any risks from conventional safety hazards should be taken into account in the decision to use such equipment."

If a very high particulate concentration in the air (~100 mg m^{-3}) is assumed containing 300 Bq ^{137}Cs g^{-1}, the resultant committed radiation dose can be calculated from the realistic stipulation that an average human breathing rate is about 5.4 10^{-3} m^3 s^{-1}. According to ICRP (1995), inhalation of 1 Bq of ^{137}Cs gives a committed dose of 3.9 10^{-8} Sv. This means that we are dealing with a dose rate of 1.2 μSv· h^{-1}.

4.5.4 Conclusions

From the calculations, it can be concluded that the ash concentrations in the fly-ash silo, in the bottom-ash containers and in the 'big bags' give the highest contributions to the extra external dose rate to workers in the power plant. If personnel is working very close to these locations throughout an entire working year, dose contributions of about 15 mSv may be expected, if Belarus soil-to-wood TFs and a deposition of 1480 kBq m^{-2} apply. In the W. European scenario, this value would be reduced with a factor of ~150 due to the lower soil-to-wood TFs. Since workers are not expected to be positioned at a distance of only 50 cm of the ash concentrations throughout the whole working year, this estimate is probably highly conservative. If a

person stands at a distance of 5 m instead, the dose rate would be reduced by a factor of at least 5, depending on the characteristics of the ash-container.
Based on calculations, inhalation doses received through routine operation of the power plant would be considered to be negligible, and respiratory protection would not be required for radiological reasons. Additional dose contributions received from contamination in the power plant should be compared with the average annual dose received by merely staying in an area contaminated with some 4 MBq m^{-2} of ^{137}Cs. This would amount to about 20-40 mSv, depending on the degree of shielding provided by dwellings. In other words, the dose increment by working in a biomass-fired power plant does not appear to be dominant compared with the doses received in the same area from environmentally distributed sources of radiation.

4.6 *External effective doses at ash deposits*

Ashes are generally not returned to the cultivation field as a fertiliser given their often caustic character. Instead the ash is deposited close to the power plant or at municipal refuse dumps. Disposal of radioactive contaminated ash should be controlled in order not to result in secondary contamination. Workforce exposure at the ash deposits was calculated using Microshield 4.10 software. Uncertainties in dose calculation within 10 - 15 % of the true situation are to be considered as very good (Microshield, 1993).

Wood ash composition is taken from Steenari (1998). Ash density was taken as 0.6 g cm^{-3}. The ash is assumed moisture-free. Soil composition was as described before. Values for carbon and oxygen are estimations made by the authors. In case uncontaminated soil is used as a shield, the following soil composition was used: 67.5 % SiO_2, 13.5 % Al_2O_3, 10.0 % H_2O, 4.5 % Fe_2O_3 and 4.5 % CO_2 (Finck, 1992).

Effective dose rate is slowly increasing with the radius of the cylindrical deposit due to self-attenuation within the deposit itself (Figure 14). The height of the deposit affects the dose rate more than the radius. Due to self-attenuation, the surface area of the deposit you are exposed to is more important than the volume. For a deposit with a radius of 30 m the effective dose rate increases gradually with a factor 2 for a height from 1 to 4 m. If the deposit is an infinite slab, the thickness of the slab does not affect the dose rate above the slab beyond a thickness of approximately two meter (also due to self-attenuation) .

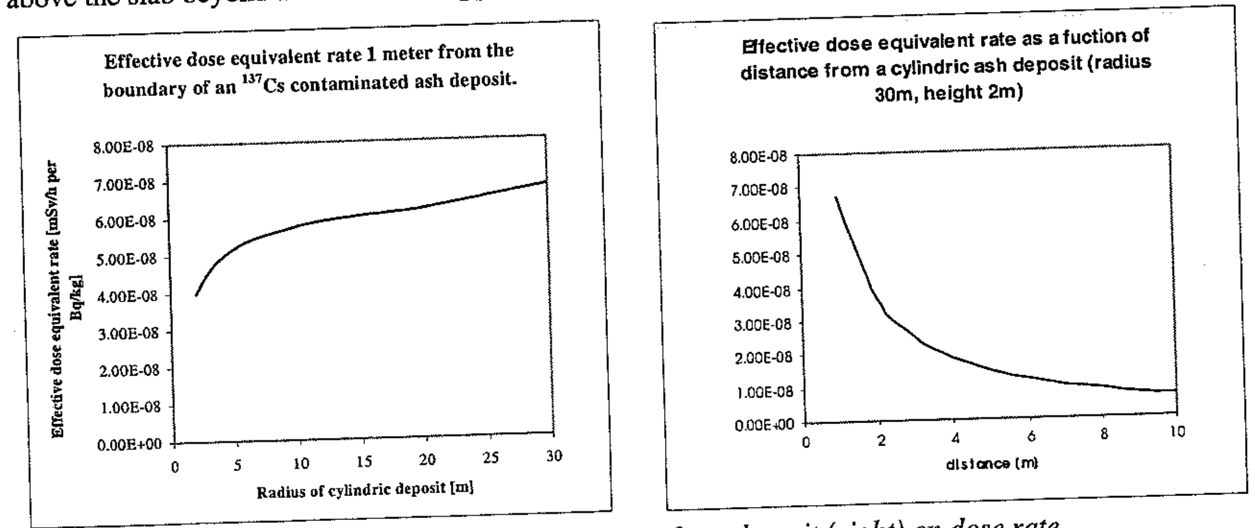


Figure 14: Effect of deposit radius (left) and distance from deposit (right) on dose rate.

Half a meter of soil above an infinite slab source of contaminated ash reduces the dose rate by a factor of approximately 1000. The distance to the surface of the deposit is an important factor when assessing the effective dose to workers (Figure 14). A dose rate reduction of a factor 5 is obtained when moving from 1 m ($6.7 \cdot 10^{-8}$ mSv·h per Bq·kg^{-1}) to 5 m ($1.5 \cdot 10^{-8}$ mSv·h per Bq·kg^{-1}) from the deposit.

A wood contamination level of 3000 Bq·kg^{-1} (Belarus TF: 2 10^{-3} m² kg^{-1}; deposition: 1480 kBq m^{-2}) contamination) will give approximately 150 000 Bq·kg^{-1} of ^{137}Cs in the produced ash. This leads to a dose rate of 10 µSv·h^{-1} or an annual dose of 20 mSv (2000 h per year) at the distance 1 m. At the distance 5 m the dose rate is 2.25 µSv·h^{-1} or 4.5 mSv annually.

In case wood is used for pulp and paper production, the ash and liquor sludge produced are disposed in a waste dump or in a landfill. Starting with a wood contamination level of about 10 Bq ^{137}Cs kg^{-1}, Ravila and Holm (1994) found that radiation from radionuclides in a black liquor holding tank amounted to 38 nSv h^{-1} at 1 m altitude. They measured the dose at 16 different waste deposits and found dose rates above background between 0.05 and 0.065 µSv h^{-1}.

4.7 *Assessment of the effective inhalation and external dose due to atmospheric discharge of ^{137}Cs contaminated fly ash from a biofuel powered heating plant*

Atmospheric release of contaminated fly ash will lead to an elevated concentration of radiocaesium in the air in the vicinity of the power plant. To assess the maximum effective internal and external dose from atmospheric releases of fly ash, a Gaussian plume model (Whicker and Schultz, 1982) has been applied in combination with dose conversion factors found in literature (ICRP, 1991, Kocher, 1983; Lindborg, 1989; Finck, 1992).

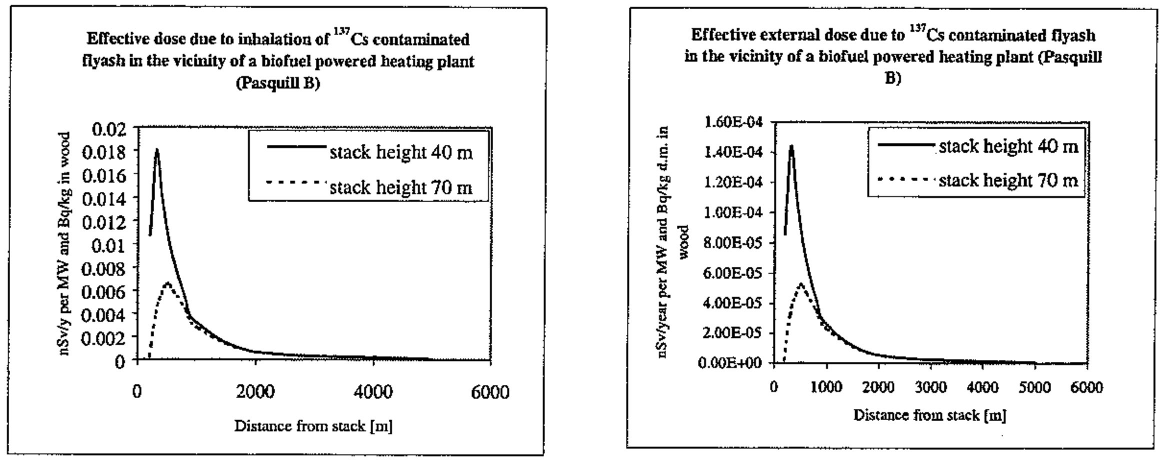


Figure 15: Effective dose due to inhalation (left) and external exposure (right) in vicinity of biofuel power plant

Modern electrostatic filtering systems collect up to 99.99 % of the produced fly ash (Information from AB Enköpings Värmeverk). According to Hedvall (1997), between 1.4 and 10 % of the fly ash is leaving the stack in Swedish biofueled power plants. The fly-ash-collection efficiency was set to 90 % in order not to underestimate the doses. It was assumed that the surroundings of the plant consisted of flat terrain and no depletion of the plume occurred due to wet or dry deposition or by gravitational settling.

Figure 15 represents the dose calculations for the atmospheric stability class (Pasquill B) for which the highest doses apply. A person standing continuously in the dose maximum near a 100 MW heating plant firing wood with a ^{137}Cs concentration of 1000 Bq·kg^{-1} would only receive an effective dose of a few µSv, due to inhalation of ash,. The dose contribution from atmospheric release of contaminated fly ash can hence be neglected for heating plant with a modern filtering system.

4.8 *Conclusions*

Dose calculations show that radiation exposure during SRC wood production and conversion will not restrain people from changing their land-use to willow SRC. On the contrary, doses received during willow cultivation is lower than in intensive agriculture since maintenance is limited. The only problem may arise in case of very high contamination levels in the fuel wood (3000 Bq kg^{-1}): external exposure of someone constantly working close to the ash collectors in the conversion unit or at the ash deposit may exceed the limit for the public. Under these conditions, doses received by the personnel should be controlled and workers may even be regarded as radiation workers.

5 Agro-technical evaluation of some potential energy crops

5.1 Crops comparison and classification

A number of crops were selected for evaluating their use as energy crop, considering different parameters: background phytotechnical knowledge and cultivation area in Belgium and/or Belarus, hardiness and adaptability to various weather conditions, potential productivity, development state of the chain(s) used for biomass valorisation. As such, five annual crops (sugar beet, winter wheat, oilseed rape, Jerusalem artichoke and sweet sorghum), one perennial crop (miscanthus: full duration: 10 y) and one perennial lignocellulosic crop (willow cultivated as SRC: full cycle: 20-25 y; internal rotation: 3-5 y) were selected. Ecophysiological (soil, water and temperature requirements) and phytotechnical indicators (rotation, soil preparation, sowing, nutrient take-up and fertilisation, weeds, pests and parasites prevention and destruction, harvest and yields) are studied. Furthermore, potential food and non-food uses and biomass energy balance are discussed. The energy efficiencies (ratio energy output/fossil energy input) are calculated from crop establishment till the useful product (wood, bio-ethanol or bio-diesel).

The main results are summarised in Table 18. An extended description was given by Goor (1998a). The three most common crops (sugar beet, winter wheat and oil seed rape) show more or less similar characteristics. They hardly cope with acid soils and require temperatures round 20-25°C for optimum growth. Nitrogen demands are high to reach acceptable yields. Since the transformation cycles (to bio-ethanol and bio-diesel) are energy demanding, the global energy efficiency is rather low (around 2,5-3) when the by-products, often used as fodder, are included. This value decreases down to 1 when only the main energy products (bioethanol or biodiesel) are considered. Used as substitute for fossil fuels in the engines, these liquid biofuels have an added value compared to wood, but their transformation cycle is energy consuming.
Jerusalem artichoke is a high yielding hardy crop, little demanding for soil and available water and able to grow in a wide range of weather conditions. The tubers can remain in the soil during winter, allowing the farmer to harvest when time and workforce are available. Energy efficiencies up to a value of 11 are reached. Crop regrowth may, however, disturb the following crop.
Sweet sorghum and miscanthus require high temperatures. The minimum germination temperature is 10-12°C (only observed late in the growing season under continental climates as in Belarus), the optimum growing temperature is between 25 to 30°C. These crops are better adapted to low latitudes where they can reach very high yields. Energy efficiencies are high (comparable to Jerusalem artichoke).
Willow cultivated as short rotation coppice shows some advantages. It can be grown on lightly acid soils. It is harvested during the winter, when farm work is available, and when all the leaves are fallen on the soil, providing nutrients for the following growing seasons. Fertilisation can therefore be reduced. As perennial crop, it limits erosion and nitrate leaching (among others). The high yields (10 to 12 t of oven-dry matter) allow reaching the highest energy efficiency (20 to 30, depending on the valorisation pathway chosen). However, water demands are high.

To summarise, sugar beet, winter wheat and oilseed rape are well-known, but their use as energy crops depends on a heavy processing industry and their energy efficiencies are low. The interest of such crops for biofuels production in a given country will depend on market structure and often food crop overproduction. Jerusalem artichoke is an interesting crop but its cultivation still faces some problems. Sweet sorghum and miscanthus cannot thrive in colder climates given their high temperature requirements. Willow seems to be the most promising crop: it is adapted to various soil and climate conditions; it is less demanding for fertilisation; it is highly efficient from an energy point of view and can be burnt in various heat and/or power plants, separately or in combination with other biofuels.

Table 18: Evaluation of some potential energy crops in terms of crop and cultivation requirements and energy efficiency

	Sugar beet	Winter wheat	Oilseed rape	Jerus. Artichoke	Sweet sorghum	Miscanthus	Willow (SRC)
Extension level (knowledge, relative area, ...)	+++	+++	++	-	+	-	+
Periodicity	Annual	Annual	Annual	annual	Annual	perennial (10 years)	perennial (20-25 years)
Optimum soil	Loam	Loam	sandy loam	**less demanding**	**less demanding**	sandy loam	**less demanding**
Optimum pH	6,8-7,2 (>5,0)	7,0-8,5	7,0 (3,8-7,8)	**less demanding**	6,0-7,0 **(less demanding)**	5,5-7,5	5,5-7,0 **(4,5-8,5)**
Optimum water supply [mm year^{-1}]	600-700	450	380-460	**less demanding**	400	500-1000	400-600
Water Use Efficiency [l kg^{-1} odm]	100-476	500	700	**high**	200-300	327	n.a.
Min. Germination temperature [°C]	3-5	0	0	0	10-12	10	5,6
Required sum of temperature [°C]	2400-2800	2500	2900	2000-3000[4]	1600-1900	n.a.	>875
Optimum growing temperature [°C]	24	20-22	<25	n.a.	30	≥25	n.a.
Sowing (planting) date (in Belgium)	20/03-20/04	01/10-01/11	<15/09	15/04	15/05 (15/04-01/07)	15/05-01/08	01/04-31/05 (<01/07)
Harvesting date (in Belgium)	01/10-01/12	20/07-10/08	20/06-10/07	**winter**	01/10-15/10	01/03-15/05	**winter**
Recommended N fertilisation [kg ha^{-1}]	150-200	120-200	120-200	**40-100**	120 (80-200)	**100-150[6]**	**60-80[1]**
Recommended P_2O_5 fertilisation [kg ha^{-1}]	80-100	50-80	80-100	60-80	60-100	150-200	**14, 10[1]**
Recommended K_2O fertilisation [kg ha^{-1}]	150-200	50-80	90-180	125-150	60-200	400	**72, 35[1]**
Average yield [*10^3 kg ha^{-1}][5]	10-17,5 (tubers)	6,4-6,8 (seeds)	2,7-3,7 (seeds)	**12-20 (tubers)**	50-85 (stems and leaves)	20-25 (stems)[2]	**10-12 (stems)[3]**
Main energy product	Bioethanol	Bioethanol	Biodiesel	bioethanol	Bioethanol + bagasse	lignocellulose	lignocellulose
Limited energy efficiency[7]	0,86-0,92	1,07	1,49	4,63	3,63		
Global energy efficiency	1,8-2,4	2,9	2,5 (5,0)	**10,9**	**10,2-12,4**	**22**	**20-30**

Advantage Disadvantage

[1] = not during the establishment year; after this period, the fertilisation has to take into account the fact that the leaves come back to the soil and provide nutrients for the next growing seasons
[2] = from year 3
[3] = average value on 3 years
[4] = value for Helianthus annuus; the rotation length for Jerusalem artichoke varies from 100 days to 9 months according to the variety
[5] = in oven-dry matter
[6] = difficult to evaluate (miscanthus is able to relocate the nitrogen from the aerial parts to the rhizomes before the winter period to use it during the following growing period)
[7] = taking only into account the energy available from the main product (bioethanol of biodiesel)

5.2 *Yield estimations for SRC and other crops for Western Europe and Belarus*

A growth model was developed and validated to estimate the potential yields of the four energy crops selected (wheat, sugar beet, oilseed rape and willow SRC) (Vandenhove *et al.*, 1998; Goor *et al.*, 1999a). The yield for willow is estimated for the R_2S_2 growing year (2-year-old roots and shoots, no cut-back after the first year) and the maximum value is hence not yet attained (about 20 % yield increase during the 3rd year). Table 19 shows the result of the simulations for two soil types, a sandy soil and a peaty soil, representative of the local conditions in the contaminated area of Belarus. Calculations were performed for Belgian and Belarus climate conditions. Climate data (average daily T°, irradiance, and precipitation) were collected at both locations.

Table 19: Potential yield (oven-dry t ha^{-1}) for a given soil type and climate conditions.

Crop	Harvested parts	Units	Belgium		Belarus	
			Sand	Peat	Sand	Peat
Willow SRC	Stems wood	Oven-dry t ha^{-1}, R_2S_2*	7.5	11.7	5.1	10.5
Sugar Beet	Tubers	Fresh t ha^{-1}	54.7	57.5	34.8	57.3
Wheat	Grain	Oven-dry t ha^{-1}	5.66	6.9	2.1	6.2
Oilseed Rape	Seed	Oven-dry t ha^{-1}	2.8	3.2	1.0	2.7

* : R= roots age ; S= stem age

The peaty soil is characterised by a high soil water reserve; the yields obtained in this case may therefore be considered as potential (non-water limited) values. On this soil type, only small yield differences between Belgium and Belarus for the four crops were obtained.

Water reserve is lower for the sandy soil than for the peaty soil and plants will suffer from water shortage. Yield of willow is reduced most due to its high water demand. The difference in yield for Belgian and Belarus growing conditions is much more pronounced on a sandy soil due to the irregular precipitation pattern in Belarus and a shorter growing season (6 months; almost no rain during 3 months). Compared to the peaty soil, yield is on average 20-30 % lower on a sandy soil in Belgium and 50-60 % on a sandy soil in Belarus.

Water balance is more important on a sandy than on a peaty soil; this was also shown by a sensitivity analysis (Table 20). The light conversion efficiency is certainly the most important factor affecting yield. Water balance comes second on a sandy soil whereas there is no effect on a peaty soil.

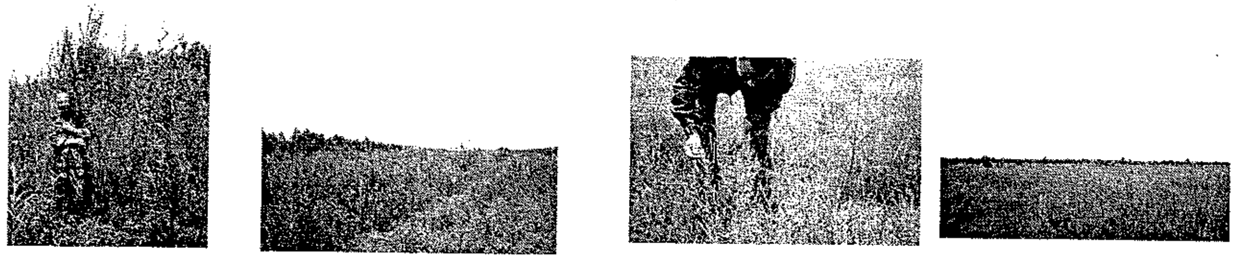
Table 20: Sensitivity analysis for effect of LAI, light conversion coefficient and water reserve on yield (t h^{a-1}) on a peaty and a sandy soil in Belarus

Parameter		Peaty	Sandy
Reference		10.895	3.857
LAI	+ 20 %	11.521	4.113
	- 20 %	10.013	3.478
Light conversion efficiency	+ 20 %	13.074	4.628
	- 20 %	8.716	3.085
Field capacity	+ 20 %	10.895	4.468
	- 20 %	10.895	3.368

5.3 *Willow growth in Belarus*

For the trials established in Belarus (section 3.3) mortality rate, stem number and height, and stem and leaf oven-dry matter (ODM) were recorded monthly between May and November 1997 and three times in 1998. Height of the plants was calculated by selecting 5 or 10 successive living plants in the same row and measuring the height of the 3 to 5 dominant stems. Stem and leaf dry matter ODM was determined by randomly choosing 3 or 5 plants, separating stems and leaves, homogenising and drying at 105°C during 24 hours. The leaf area index (LAI) was derived as a function of total leaves oven-dry weight from curves established in both Belgium and Sweden. In 1997, the total plot was harvested during the cutback operation. The 1998-yield was estimated using stem height, weight and stem number per unit area.

As already mentioned earlier and clearly shown by Figure 16, the willows on the sandy soil were hardly growing (Savichy) or died off completely (Masany). Since weeds were not completely removed before plantation at Masany, they were hampering willow development. At Savichy peaty, willows performed well.



Peaty soil

Sandy soil

Figure 16: The test sites at in Savichy (sandy and peaty soils) in June 1998

5.3.1 Crop mortality

Table 22: Mortality estimations (%) for four willow clones at Savichy sandy and peaty

	Sandy soil		Peaty soil	
	1998	Δ	1998	Δ
BJORN	33,5 ± 23,0	17,5	26,1 ± 10,8	11,5
JORR	47,0 ± 13,1	39,4	18,0 ± 9,0	4,5
ORM	17,3 ± 6,7	8,9	19,7 ± 6,6	8,8
RAPP	30,4 ± 9,8	23,5	22,3 ± 6,8	6,1

Δ = mortality progression between October 1997 and May 1998

Mortality on the sandy soil was between 20 and 50 % each year, depending on clone (Table 21). On the Savichy peaty soil mortality rates are more acceptable (~20 % in the establishment year and a 5-10 % reduction in mortality thereafter (1997). The difference may be explained by the higher soil water reserve of the peaty soil. At Masany-Peaty, mortality was only about 10 %.

5.3.2 Growth parameters

Plant height at the Savichy Peaty soil ranged between 2 and 3.5 m, which is satisfactory. For the sandy soil plant height varied between 0.5 and 1.2 m.

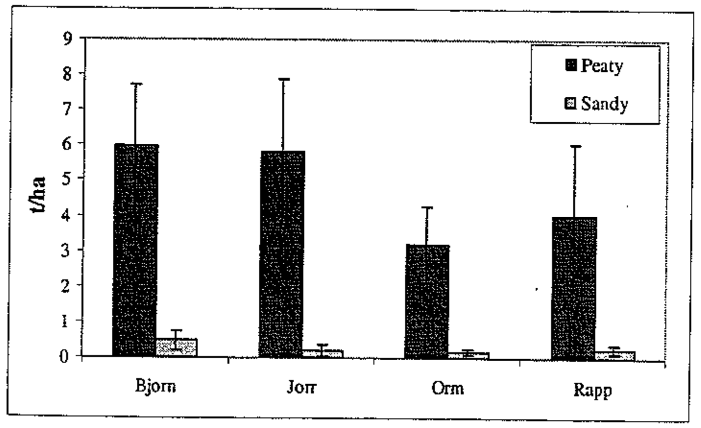


Figure 17: Willow yield (1998) at Savichy sandy and peaty

Yield in 1997 (cutback yield, R_1S_1) was about 0.25 t ha^{-1} for the sandy soil and about 1.4 t ha^{-1} for the Savichy peaty soil. In 1998, yield ranges between 3 (Orm) and 6 (Bjorn and Rapp) t ha^{-1} on the Savichy peaty soil (Figure 17), the higher value being comparable with yield obtained in Western Europe for the first year after cut back. Due to competition with weeds, estimated wood yield was only about 1 t ha^{-1} at Masany Peaty. As is clear from Figure 16, willow does not grow on the poor sandy soil at Savichy. The clone Bjorn seems to be best adapted to the limited water supply on the sandy soil (not significant).

5.3.3 Concluding remarks

Among the four field trials initially planted in 1997, only the peaty soil in Savichy gives sufficiently high yields. The sandy soil, where willow died off, could maybe better be reforested with little water-demanding *Pinus sylvestris* or cultivated with drought-tolerant grasses.
From the bad performance of the willows at Masany-peaty, it is clear that initial weed removal (before plantation) is indispensable.

Although a high variation in yield is observed, crop selection seems nevertheless important. Bjorn and Rapp have statistically higher yields (at 10 % level) compared to the other varieties (at 10 % level)

Potential yields estimated for a R_2S_2 crop are comparable for Western European and Belarus conditions when Salix is grown on a peaty soil. On a sandy soil, the yield potential is about 30 % lower in Belarus.

6 Ecological sustainability of willow and other energy crops

The use of biofuels such as biomass and liquid biofuels for energy production and transport fuels, may reduce the fossil fuels demands to meet our energy requirements. This may have positive environmental effects as a reduction in CO_2 emission. Apart from a possibly positive energy balance and a reduced emission of green house gases, other ecological criteria may have to be considered when evaluating energy crops. In a life cycle analysis for a number of energy crops, Biewinga and van der Bijl (1996) evaluated additionally the emission of acidifying and ozone depleting gasses, leaching of minerals to soil and water, emission of pesticides, soil erosion, ground water depletion, use of resources, waste production and contribution to biodiversity and landscape values. Evaluating all these criteria is outside the scope of our study. We only engaged in evaluating carbon and energy balances and the nitrogen leaching under different cropping systems. Some consideration will also be dedicated to the amount of (radioactive) waste produced.

6.1 Carbon and energy modelling

Biofuels are often described as 'carbon neutral', since the carbon sequestered in the biomass is released during the conversion so that there is no net increase in carbon in the atmosphere from energy production from fossil fuels. However, this view does not account for the amount of fossil fuels used in the production of the energy crop, and in the construction and maintenance of the machinery and the conversion plant.

The carbon and energy balance model (CEBM) used in this study (Matthews *et al.*, 1994) is particularly rigorous in including direct fuel use in production, indirect fuel use in machinery and materials manufacture and extraction costs of fossil fuels. Activities involved in production were also included. It therefore gives a complete picture of the production of biofuels, provided sufficient data are available. Where data were not available in the detail required for the modelling, estimates from published studies were used. As far as possible, similar assumptions and values for the parameters were used as for the economic modelling (Chapter 7). The CEBM does not cover conversion. Values for the CEB for construction and maintenance of the conversion plant have been taken from recent studies (Gover, 1996; Bates *et al.*, 1997; Mortimer, 1999).

In the modelling process, all the operations involved in the biofuel production are identified and are the same as those used for the economic modelling, so that there is consistency throughout the project.

The total energy requirements and CO_2 emissions include contributions from
- direct fuel usage in production, e.g. in farm and transport machinery
- fuel extraction costs associated with fuel usage
- indirect fuel costs associated with manufacture of materials and machinery in production
- indirect fuel costs associated with construction and maintenance of conversion plant
- direct fuel costs for running the conversion plant
- indirect fuel costs from materials used in the conversion plant

The data on operations performed in the biofuel production are the most up-to-date information available. They were collected for the RECOVER project by the partners. The data on the amount of energy required to produce machinery and materials is from the UK model. These data were the best available at the time the model was written, but as stated by the author the data used are derived from results obtained 20 years ago. It is possible that if data were available for more modern processing techniques, the energy costs of production may be reduced. No data were available for the energy required for production of machines and materials in Belarus, and these systems were therefore not modelled separately from the W. European cases.

The output of this CEB study is an estimate of the energy requirements and CO_2 emissions from production of 1 unit of the final product. In the case of electricity from wood, this is the production of 1 kW electricity. In the case of liquid biofuels from oil seed rape (OSR), winter wheat (WW) and sugar beet (SB) this is from travelling 1 km in a car.

6.1.1 Short rotation coppice

Table 22 gives energy and carbon data for energy production from SRC. Specifications were the following: area 10 ha (10000 cuttings per ha), cut and chip harvesting (2.3 h ha^{-1}), yield 12 t ha^{-1}, no fertiliser, weed control at establishment and after harvest, spraying after each harvest, crop duration of 19 years, transport distance 40 km. The plant capacity was 33.4 MWe, with a conversion plant efficiency of 39 % and an availability of 80 %. Power plant life time was 20 years.

Table 22: Energy input and CO_2 emissions for SRC

Operation	**Energy cost** kWh kWhe^{-1}	**CO_2 release** g kWhe^{-1}	**Direct CO_2 release** g kWhe^{-1}
Cultivation	*0.059*	*19.3*	*8.2*
Establishment	0.014	6.3	1.1
Management	0.012	4.1	0.1
Harvesting	0.033	8.9	7.0
Transport	*0.032*	*8.4*	*6.7*
Conversion	*0.02**	*4.3**	*4.3**
TOTAL	**0.11**	**32.0**	**19.2**

*: Data from Mortimer (1999)

The results show that, for this scenario, the harvesting uses most energy and emits most CO_2 at the production site. If stick harvesting would be applied (1.8 h ha^{-1}), the harvesting itself would require almost the same amount of energy and produce similar amounts of CO_2. About twice the amount of energy and CO_2 would however be needed and produced during storage and chipping.

Inclusion of spraying after each harvest gives rise to a significant increase in the energy requirement.

The assumed transport distance is 40 km. Doubling the transport distance doubles the amount of energy used and carbon released in transport. In the above example, a 80 km journey would lead to the transport costs being twice the harvest costs, and to an overall increase of 32 % of the total energy cost. It is unlikely that SRC will be transported further than 80 km to the conversion plant.

Energy requirements and CO_2 production are considerably lower at the conversion site than during production.

At first glance, the energy requirements and CO_2 emissions calculated seem higher than those in existing published work. For example, Bates *et al.* (1997) compare CO_2 emissions for SRC production in four countries. The figures range from 17-27 g CO_2 kWhe^{-1}. Biewinga and van der Bijl (1996) report values between 13 and 16 g CO_2 kWhe^{-1}. The emissions quoted are the direct emissions from fuel use in production only, together with the emissions from construction and operation of the conversion plant. Emissions from the construction of machinery are not included. When only considering direct emissions a value of 19.2 g CO_2 kWhe^{-1} is obtained, which is in close agreement with published data.

For comparison, Table 23 shows that the CO_2 emissions for a wood fired plant are about a factor of 11 less than for a gas fired plant and about a factor of 25 less than a coal fired plant. Only about 0.15 kWh fossil energy is required to produce 1 kWh electricity from wood fuel gasification. The reason why this is much lower than for fossil fuel plant is that wood is not a fossil fuel, so the only fossil fuel consumed is that required to produce the wood. For gas and coal plant the fuel used in the conversion plant is a fossil fuel.

Table 23: CO_2 emissions and fossil fuel needed for biofuel and fossil fuel fired power plants

	Wood Fired	**Gas fired**	**Coal fired**
CO_2 kWhe^{-1}	40	440	980
KWht kWhe^{-1}	0.15	2.4	3.5

6.1.2 Liquid biofuels for transport fuels

6.1.2.1 Wheat

The simulations for the W. European large scale production of bioethanol from wheat (Chapter 7) was used as the basis of the operations carried out for production of wheat for biofuels. Data were provided by UCL and IPEP and fertiliser application rates were according to Audsley *et al.* (1996). At the conversion site, data from Gover (1996) were used.

The specifics were as follows: yield 8 t ha^{-1}, area 1 ha, 7 applications of pesticides and growth regulators, NPK 240-26-50 kg ha^{-1}, a medium combine harvester (1.1 h ha^{-1}).

The energy requirements during production mount to 24.5 GJ ha^{-1} of which 9.1 GJ is linked to fuel use and 13.5 GJ ha^{-1} for fertiliser and pesticide production. This is in clear contrast with the situation for the wood fuel production. The value obtained is in good agreement with the energy requirements reported elsewhere: 18.1 (Gover, 1996) and 21.6 GJ ha^{-1} (Audsley *et al,*. 1996).

In comparison with the two other studies the CO_2 emissions obtained in our study are high: 491, 51.4 and 176 kg CO_2 t^{-1} wheat, respectively. This is partly due to differences in fertiliser application rate (only 50 Kg N by Gover, 1996) and different CO_2 to N conversion factors: 12.8, 2.3 and 1.57 kg CO_2 per kg N, respectively. The high value in our study is from Matthews (1994) and may be based on older data.

Total emissions for liquid biofuel productions are given in Table 24. The energy requirements during production are taken from our study and for the CO_2 calculations the most appropriate CO_2 to N conversion factor is taken from Audsley *et al.* (1996). For energy requirements and CO_2 emissions during transport of wheat and bioethanol (to retailers) and during processing, we rely on Gover (1996).

Table 24: Total emissions for liquid biofuel production from wheat

	Energy MDI GJ^{-1} ethanol	**g CO_2 GJ $^{-1}$**
Agriculture	271	21000
Processing- natural gas	779	41896
Transport	15	1062
Distribution	8	561
Total	**982**	**59800**

Energy balance for bioethanol is very close to 1, for the scenario considered. The ratio will improve if credits for straw are included but, as stated above, this is not thought feasible for a conversion plant at the large scale.

CO_2 emissions from agriculture can vary by a factor of at least 3 due to the importance of the contribution from fertiliser production and due to the variation in the estimates of amount of fertiliser applied and emissions of CO_2 per kg fertiliser produced. The total emissions of CO_2 are dominated by the emissions from processing, so that the variation in agricultural emissions leads to an uncertainty in the overall emissions of about 16 %.

Comparison with fossil fuels

Bioethanol is most likely to be used as a transport fuel, either as a petrol extender or a high percentage ethanol blend. We have assumed that the bioethanol will be used in a car petrol engine as a petrol extender. It is beyond the scope of this report to consider the relative merits of bioethanol and petrol in detail, and we assumed that bioethanol has the same performance as petrol in a blended fuel. The parameter of importance for transport fuels is the fuel consumption per distance travelled, and here we have considered MJ km^{-1} and the associated CO_2 emissions g CO_2 km^{-1}.

If the energy value of bioethanol is taken as 23 MJ L^{-1}, then the fuel consumption assumed is 10 L 100 km^{-1}. This is in the range of the 8 to 10 L 100 km^{-1} quoted for a modern petrol engine on the overall test results under the new EC standard. The CO_2 emissions for the same engine are quoted as 180-226 g CO_2 km^{-1}. Thus the direct use of petrol or bioethanol (Table 25) leads to comparable energy use and CO_2 emissions. Since the combustion of bioethanol is considered CO_2 neutral, then the CO_2 emissions to be compared are the indirect emissions from the bioethanol and the total, direct and indirect, emissions from the petrol. If extraction costs for the fossil fuel are considered ~10 % of the direct costs, then the total CO_2 emissions for petrol will be 200- 249 g CO_2 km^{-1}, compared with 140 g CO_2 km^{-1} for bioethanol, less than a factor 2 reduction. However, more pessimistic assumptions (higher C/N conversion factor as proposed by Matthews, 1994) erode this advantage.

Table 25: Partitioning of energy requirements and CO_2 production between direct biofuel and indirect fossil fuel use during travel with bio-ethanol

	Energy MJ km^{-1}	**g CO_2 km^{-1}**
Direct biofuel use	2.3	(181)*
Indirect fossil fuel use	2.3	140

*Combustion of biofuel considered carbon neutral, since CO_2 released is the same as the CO_2 sequestered during wheat growth.

6.1.2.2 *Sugar beet and oil seed rape*

There were no published data available in the detail required to run the CEBM for sugar beet (SB) and oil seed rape (OSR). For winter wheat (WW) no results were available from Gover (1996) since he considered only sugar beet and oil seed rape. However, some unpublished data (Walker, 1999) suggest that the overall energy requirement for production of bioethanol from sugar beet will be similar to that from wheat. For OSR a summary of the Gover analysis is given below. These data were used because they are from the same study as some of the wheat data (so a comparable methodology has been used) and because the study follows through the production of the liquid biofuel to its end use as a transport fuel.

Table 26: Summary of energy requirement and emissions from the production, transport and distribution of biodiesel from winter oil seed rape.

	Energy, MJ GJ^{-1} of RME	**g CO_2 GJ^{-1} of RME**
Agriculture		
Production	415	10607
Oil extraction	230	13026
By product- cattle cake	(85)	(4410)
Processing		
Using natural gas	319	11954
Transport		
Seed and oil	10	707
Distribution of RME	5	357
TOTAL	894	32242

Table 26 shows that the energy ratio for RME is 1.1, so that almost as much fossil fuel is used to produce RME as energy is obtained from combustion of RME. However, again the energy balance can be significantly improved if the straw is utilised.

Comparison with fossil fuels

Biodiesel can be used in existing diesel engines without modification, replacing mineral diesel. We have adopted the assumption by Gover (1996) that engine performance is the same for mineral and biodiesel, except that 5 % greater volume of biodiesel is required.

Table 27: Partitioning of energy requirements and CO_2 production between direct biofuel and indirect fossil fuel use during travel with bio-diesel

	Energy MJ km^{-1}	**g CO_2 km^{-1}**
Direct biofuel use	1.8	(142)*
Indirect fossil fuel use	1.6	59

* Combustion of RME is considered carbon neutral, since the CO_2 released was sequestered during the growing of the OSR.

The energy use per km corresponds to a fuel consumption of 5.61 L 100 km^{-1} for RME. Data for a modern diesel engine gives a range of mineral diesel consumption of 5.7-10.6 L 100 km^{-1}, and associated CO_2 emissions of 151-250 g km^{-1}. With a mineral diesel consumption of 5.7 L 100 km^{-1} and if extraction costs are taken to be about 10 %, the total CO_2 emissions for mineral diesel are 166 g CO_2 km^{-1}. The use of RME could therefore reduce the CO_2 emissions by up to a factor of three.

6.1.2.3 *Conclusions*

For the wood fuel system, there are still considerable uncertainties in the estimates for the energy and carbon balance. However, when compared with gas fired and coal fired power plants, energy requirements are, respectively, a factor 16 and 23 lower. CO_2 emissions from wood fuel burning are a factor 11 and 25 lower than for gas and coal burning.

For the liquid biofuels, the energy efficiency is close to one. Reduction of CO_2 emissions when using biofuels as transport fuel is maximally about a factor 1.5 to 3. This is in agreement with results from the study by Biewinga and van der Bijl (1996) that also found that electricity-production routes have much better energy budgets and avoid more CO_2 emissions than liquid fuel routes.

6.2 The problem of nitrate leaching

The cultivation of winter wheat, sugar beet and oil seed rape for bioethanol and biodiesel production might involve intensive agricultural methods, with considerable inputs of fertilisers and agrochemicals, which production involves release of greenhouse gases and waste water. In contrast, SRC is grown with minimal input of fertilisers and agrochemicals, and hence emissions will be minimal.

Nitrate is the main element in fertilisers and N-requirements depend on a number of factors; therefore optimal nitrogen application rates are not easy to estimate. Sometimes therefore, nitrogen is applied in excess to plant consumption, and nitrate leaching may occur. The nitrate leaching risk depends on land utilisation, being higher for arable farming systems (especially when soil is left bare in winter) than for grasslands or natural vegetation systems, such as forests, where growth and hence uptake of water and nutrients is almost continuous. Similarly, perennial agricultural crops as SRC, may limit the risk of nitrate leaching.

6.2.1 Monitoring of nitrate leaching at experimental sites

The nitrate concentration in the soil solution was monitored using a capillary wick lysimeter. Experimental plots (dystric cambisol) where situated close to the experimental farm of UCL in Louvain-la-Neuve (Belgium) (Goor *et al.*, 1999b). Two samplers (replicates) were installed under SRC (SRC I and SRC II, R_4S_1 in 1997 and R_5S_2 in 1998) and two under a field where maize was grown in 1997 and wheat in 1998 (Crop I and Crop II). Soil solution was collected and analysed between January and June 99. The dates for which no water could be collected do not appear in the Figure 18.

Globally, the NO_3^- concentration in the soil solution is 2 to 4-fold lower under the SRC plantation than under the crop for this experiment. Moreover, the NO_3^- concentration is below the threshold level for potable water (50 mg L^{-1}) only for coppice.

The amount of water collected under a SRC stand was also considerably lower than under the other crops, probably due to the high transpiration rates of coppice. Extra nitrogen requirement is low, partly due to recycling by litter fall. The annual litterfall is estimated to about 4-6 t ha^{-1}. With a leaf N nitrogen content ranging from 2.0 to 3.5 % at senescence, about 80-200 kg N ha^{-1} is returned annually. Nitrogen supplies therefore only have to compensate for the exportations of N from the system due to stem harvests (60-80 kg N ha^{-1} $year^{-1}$).

Previous studies in Sweden (Perttu and Kowalik, 1989; Ledin and Willebrand, 1995) and England (Hall *et al.*, 1996) have shown that the NO_3^- leaching risk under a SRC plantation is very low, even in the case of intense fertilisation. In drier regions, however, even limited NO_3^- application may result in high concentrations in water. If the NO_3^- stock from the previous crop is high, SRC will not be able to reduce the nitrate leaching at the beginning of its development, due to its relatively low N requirements at that point in time.

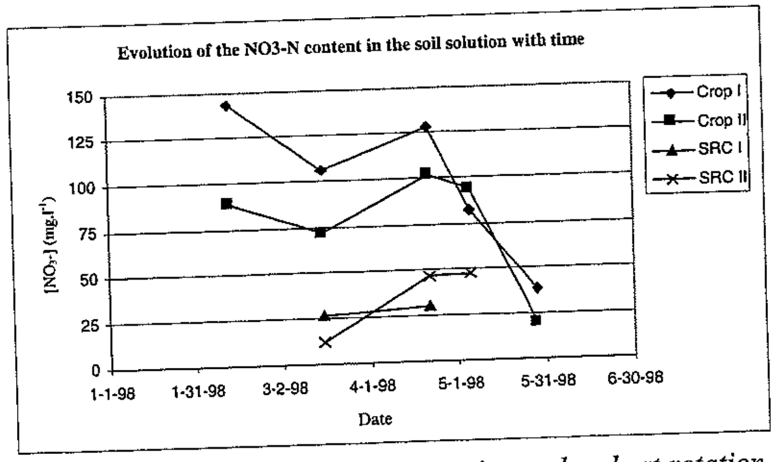


Figure 18: Evolution of the soil solution nitrate concentration under short rotation coppice and common agricultural cropping system (Crop I & II). I & II are replicate measurements.

In conclusion, SRC is a suitable crop for nitrate sensitive areas for its limited fertilizer requirements and its extensive rooting system. It could also be used as a buffer strip for intercepting nitrate runoffs from agricultural land. The high transpiration rate of SRC, partly responsible for limited nitrate leaching, may, however, result in soil drying, which may be worrying, if the SRC is introduced in wet ecosystems with high ecological value.

6.3 Waste generation and other ecological criteria

The most important 'real' waste product is the ash that is left after gasification or combustion. In principle, these ashes can be used as fertilisers but may have to be improved before return to the field, given their often-caustic character. In actual practice, ashes are often dumped. The by-products from the other liquid biofuel conversion routes are often used as animal fodder. The ashes from OSR and WW straw burning undergo the same fate as the SRC-wood ash. Table 12 gives an overview of the amounts of waste-considered side produced during conversion. This matter will be discussed in more detail in Chapter 7.4.

For the discussion of other possible positive or negative ecological impacts we extract from the study by Biewinga and van der Bijl (1996). OSR, SB and WW were found to score low on several ecological criteria. This is predominantly linked with the fact that they are intensively cultivated. High fertilisation will lead to a higher emission of acidifying and ozone depleting gasses and mineral emissions. The use of pesticides is highest in WW cultivation and lowest in SRC. In general annual crops cause greater erosion risks than perennials. Erosion risk is highest for SB and lowest for SRC. As to crop evaporation differences between crops seems not to be impressive.

6.4 Conclusions

The general assessment of the ecological sustainability for the different crops considered is the following. OSR, SB and WW score generally very low. Their connected conversion routes, leading to liquid biofuels, have a low energy efficiency (close to 1) and the reduction of CO_2 emissions when using biofuels as transport fuel is maximally about a factor 1.5 to 3. Mineral and pesticide emissions are high and erosion risk may be pronounced (SB).

For electricity production from SRC, the energy efficiency is high and the CO_2 emissions from wood fuel burning are a factor 11 and 25 lower than for gas and coal burning. Pesticide and fertiliser use is limited

7 Economic sustainability of cultivation and conversion of energy crops

When a new land-use option is proposed, the economic sustainability of the proposed system is as important as its radiological acceptability. The RECOVER project aims to assess the economic viability of a number of energy crops on contaminated land. In practice, social and political considerations will certainly play an important role in the evaluation of this new land use option, positively (e.g. by giving a subsidy to farmers converting to alternative crop production) or negatively (e.g. people unwilling to buy products from contaminated areas; people reluctant to engage in something unknown. It is equally important that a market exists or is developed for the new product. Evaluating these latter considerations is, however, beyond the scope of our project.

The energy crops under consideration in present study are Short Rotation Coppice (SRC), Oil Seed Rape (OSR), Sugar Beet (SB) and Winter Wheat (WW). The latter three crops were chosen because they are already grown in Belarus and they can be converted to liquid biofuels in a straightforward process, which has already been demonstrated. In particular, the production of energy from crops in Western Europe (represented by the UK and Belgium) is compared with that in Eastern Europe (represented by Belarus).

The economic modelling of energy production from crops was done with RECAP (coppice), CRISP (other crops) (models developed by ETSU) and ECOP (UCL model). For more information about the models (characteristics, parameters calculated, parameter lists,...) we refer to Annexes 1-3.

Economic analysis was performed for Western European and CIS conditions. Important system parameters for Western/European and Belarus comparison are alluded upon below (Table 28 and 29) and are discussed in some detail in Annex 1 (SRC) and 2 (annual crops). Different types and scales of conversion systems for production of heat and electricity were studied. Similar systems were modelled for the Belarus and Western European cases. Sensitivity analyses were performed both at the level of crop production (e.g. yield, harvesting methods, grants, energy crop price) and at conversion (cost, energy crop price, plant availability). Data for the Western European scenario came from UK and Belgium and data from Belarus were collected by RISOE/IPEP. Extra costs arising with a contamination scenario (disposal costs and compensation for doses) are evaluated in Chapter 7.

7.1 Modelling short rotation coppice

7.1.1 Comparison of Belarus and Western situations

From Table 28 it is clear that there are important differences in parameter estimates for modelling SRC-economics between Belarus and Western Europe. The main differences are

- labour costs are a factor of at least ten lower in Belarus
- at present no grants are available in Belarus
- farm machinery costs lower in Belarus by up to a factor of five
- domestic heat and electricity prices are much lower in Belarus
- boilers for heat production are cheaper by a factor of three to five in Belarus

Table 28: Factors important in the modelling of SRC economics and their respective values for Belarus and Western Europe.

Factor	Belarus	Western Europe	Comment
labour cost	0.3-1.6 EUR hr^{-1}	6- 22 EUR h^{-1}	A factor of at least 10 lower in Belarus
farm machinery cost (tractor)	17 kEUR	45 kEUR	A factor of 3 to 8 lower in Belarus, depending on the machine
wood fuel price (from residues)	10 EUR odt^{-1}	20 EUR odt^{-1} 40-60 EUR odt^{-1}	Price at the roadside Price for chipped and delivered.
annual land rent	0	UK 225 EUR ha^{-1} and up; Belgium 75 upwards (average 150)	Land in the contaminated zone cannot be used for food production and is given a zero opportunity cost.
Production grants	0	Establishment grants UK: <1500 EUR ha^{-1}; B: 0 at present; Set aside payment UK ~ 450 EUR ha^{-1}; B: 230-420	Grants are in place in W. Europe to encourage diversification by farmers and to establish fuel supplies for biomass fuelled plant.
heat conversion plant cost (for 300 kW gasifier)	115-160 EUR kW^{-1}	300 EUR kWh^{-1}	
heat conversion plant cost (for 3 MW boiler)	55-100 EUR kW^{-1}	150-200 EUR kW^{-1}	
Electricity conversion plant capital costs	not known, estimate 500 EUR kW^{-1}	1500 EUR kW^{-1} installed capacity	The W. European value is predicted for commercial gasification plant at 30 MWe. No plant exists in Belarus. If the plant could be built in Belarus, we assume its cost could be up to 3 times lower than in W. Europe, in line with the relative costs of the heat plant.
Electricity price	0.034 EUR kWh^{-1}- industry 0.0032 EUR kWh^{-1}- domestic	0.045-0.12 EUR kWh^{-1} for renewable energy	The Belarus industry rate is near the W. Europe standard electricity price. The domestic rate is a factor of 10 lower. There is no price support for renewables currently in Belarus.
heat price	0.03 EUR kWh^{-1}- industry 0.001 EUR kWh^{-1}- domestic	About 0.03 EUR kWh^{-1}	Again, the domestic rate is much lower in Belarus than in the UK, and no heat schemes would be viable with these rates.

7.1.2 Coppice production

Best estimates for large-scale-production costs, excluding grants and opportunity costs (Annex 1: 3.5 and 3.8, for Belarus and W. Europe, respectively) are presented in Table 29. Yield is 12 odt ha^{-1} in each case. Table 29 shows that for similar cutting costs (0.045 EUR) for Belarus and W. Europe, and if establishment and yield are the same in both situations, the larger net margin and internal rate of return (IRR) will be attained in Belarus. This is not surprising, since they have lower costs as seen above. However, if the yield in Belarus does not reach 12 odt ha^{-1}, but is nearer 6 odt ha^{-1}, then the net margin achieved in Belarus will decrease to about 49 EUR ha^{-1}. For the small-scale production systems (Belarus case: Annex 1: 3.4) the net margin is 170 and 67 EUR per ha for a yield of 12 and 6 odt ha^{-1}, respectively. Since the opportunity cost of the land can be put to 100 EUR ha^{-1} (gain from 1 ha wheat), farmers will be reluctant to cultivate coppice under less favourable conditions unless their land is exempted from crop production.

For Belarus a wood fuel price of 10.2 EUR odt^{-1} was quoted. However, at this price production was never profitable. Even at 20 EUR odt^{-1}, a slightly positive net margin of 52 EUR per ha was only obtained for small scale production and a yield of 12 odt ha^{-1}.

The W. European situation without grants shows a positive IRR and a net margin which just exceeds the opportunity cost of 225 EUR ha^{-1} assumed for the land. However, these data assume best practice in production, and no storage costs. This has not yet been achieved in the UK at least. In the UK grants are required to offset the risk of establishment of what is seen as a novel crop, and the net margin is only seen as sufficiently attractive if the set aside grant can be claimed as well.

Table 29: Production costs and system profitability parameters for growing SRC in W. Europe and Belarus

Operation	Belarus	W. Europe	Comments
Establishment, EUR ha^{-1}	776	1500	Assuming cuttings from Sweden at 0.045 EUR per cutting for both situations
Management, EUR (ha*y)$^{-1}$	8	24	
Harvesting and chipping, EUR odt^{-1}	7 (24)	11	Belarus low value assumes high rate chipper with low cost. High value is slow chipper together with high capital cost.
Storage, EUR odt^{-1}	0	0	
Transport, EUR odt^{-1}	2.6	5	
Fuel revenue, EUR odt^{-1}, delivered to plant	40	60 (40)	Fuel price set at 40 EUR for W. Europe for direct cost comparison
Net margin, EUR ha^{-1}	192 (38)	226 (51)	
IRR, %	21 (6)	12 (5)	

7.1.3 Conversion of short rotation coppice wood

A range of possible "biomass to energy systems" have been modelled for SRC (Table 30). These cover the different conversion scales and the different technologies which we think might be applicable in Belarus and Western Europe. Both biofuel conversion systems to heat and electricity are modelled for Belarus. Systems using biomass for heat in Belarus are a medium scale heating boiler, a small scale gasifier for heating and a 'cluster' of heating boilers. Biomass is not currently used for electricity production in Belarus, and much of the equipment used in Western Europe for electricity production is still at the pilot stage. However, potentially biomass could make a contribution to electricity production in Belarus. Three systems were therefore modelled: the 8 MW demonstration scale gasifier, an estimate for a 30 MW commercial scale gasifier and a small scale 150 kW gasifier. These systems were in general based on Western European cost data, but in the sensitivity analysis the effect of reducing the cost due to the equipment becoming commercial and being manufactured in Belarus was considered. Small-scale systems were modelled because they could provide decentralised energy production in the remote areas of Belarus.

One outstanding difference between the Western European and Belarus situation is that in Western Europe the SRC schemes often generate electricity. The interest in electricity generation in W. Europe is often political in origin, with governments aiming to replace some of their generation capacity with renewable sources. For example in the UK a price support offered for electricity generated from renewables, has concentrated effort on electricity generating schemes. For medium scale schemes, at about 8 MWe, the W. European scheme is a gasification scheme for electricity production. For small scale systems, we have modelled the 150 kW Belgian gasifier, which is for electricity production. Additionally, a small scale 330 kW gasifier used for heat production in the UK was modelled, for direct comparison between the West and Belarus.
Details on capital costs of the power plant are given in Annex 1.

Table 30: Conversion scenarios modelled

Conversion technology	Belarus	UK	Belgium
HEAT			
Large scale, 28 MW(t)	X		
Medium scale, 3 MW(t)	X		
Small scale, 330 kW(t)	X	X	
ELECTRICITY			
Large scale, 30 MW(e)	X	X	
Medium scale, 8 MW(e)		X	X
Small scale, 150 kW(e)	X		X

The conversion of wood fuel to heat is well known in Belarus, and a range of boiler sizes and small scale gasifiers are in operation, fuelled with forest residues. Information from Belarus has therefore been used to estimate the economics of a SRC fuelled system. The main parameters affecting the economics are the price of the input fuel, the price obtained for the heat and capital cost and utilisation % of plant capacity. None of the conversion systems modelled was economic at the domestic heat price (Table 31).

The data from Belarus quote an utilisation of plant capacity of about 16 % for the boilers and gasifiers. This equates to seasonal heating over a small proportion of the year. This seems a low estimate for utilisation, both in terms of return on capital investment and in terms of the length of the heating season for Belarus. We have therefore run sensitivity analyses with higher utilisation rates.

The price for fuel wood in Belarus quoted is 10.2 EUR odt^{-1}. We speculate that this is the price paid for wood collected from the forest. Our calculations show that using Belarus machinery and labour, the wood could be extracted from the forest, chipped and transported to the power plant for about 28 EUR odt^{-1}. This is the cheapest we believe wood fuel could be delivered to a plant of any commercial size. Our calculations for production of fuel wood from SRC indicate that for the producer to make his target IRR, which generally equates to a small net margin per hectare, the price of delivered fuel would be about 40 EUR odt^{-1}. In most of our scenarios we have therefore used 40 EUR odt^{-1} as the minimum fuel price for determining if a SRC scheme would be profitable.

The large scale boilers in Belarus are also profitable at W. European capital cost if availability is ~80 %.

Table 31: Summary of economics of conversion of SRC for heat production

Scheme	Capital cost MEUR	Capital cost, EUR per kW installed	Availability (%)	Fuel price, EUR odt^{-1}	Heat price, EUR kWh^{-1}	IRR, %
Small scale gasifier						
• Belarus, 350 kW	0.02[§]	130	16	40	0.026	20
		130	60	40	0.026	72
• UK, 380 kW	0.115	300	80	50	0.03	22
Belarus medium scale boiler, 3 MW	0.38	100	16	40	0.026	12
			80			42
Belarus cluster of boilers, 28 MW	3.6	100	80	40	0.026	59
	10.8*		80	40	0.026	22
	14.4**		80	40	0.026	16

Belarus cost as given by Grebenkov (1997) times 3 * or 4**; §: if the cost for 350 kW gasifier with 16 % availability is estimated at 10 % to 50 % of the European cost, none of these systems is profitable (neg. IRR)

For electricity production from SRC (Table 32), we have again used a fuel price of 40 EUR odt^{-1}. The capital and running costs of these plants are much more speculative, since they are based upon projections of costs of commercial plants in W. Europe, and upon assumptions about the relative costs of building a plant in W. Europe and Belarus.

The main barrier for implementing any of these schemes, however, is the very low price paid by domestic consumers for heat and electricity in Belarus. None of the schemes will be profitable at current electricity and heat prices in Belarus, even with low capital costs and high utilisation. For heat, the industrial price in Belarus is similar to the price expected in W. Europe, and so heat schemes aimed at industrial users are viable in Belarus. For electricity, the industrial price in Belarus is similar to the standard price for electricity in the W. Europe. However, the schemes currently in place or planned in Europe receive substantial price support for producing energy from renewable sources. These prices will probably not be achieved in Belarus. Therefore, the schemes will only be viable if plant can be manufactured in Belarus, and if the plant is at the stage of 'tried and tested technology'. Alternatively, a capital grant for the construction would be required. Even so, the model shows that the annual balance of costs and revenues is only positive if the electricity price is at least 0.05 EUR kWh^{-1}.

Table 32: Summary of economics of conversion of SRC for electricity production

Scheme	Capital cost MEUR	Capital cost, EUR per kW installed	Avail. %	Fuel price EUR odt^{-1}	Elec. Price, EUR kWh^{-1}	IRR, %
Small scale gasifier, 150 kW						
• Belarus	0.04	267	80	40	0.05	10
					0.034	< 0
• Belgium	0.17	1120	12	58	0.132	<0
UK medium scale gasifier, 8 MW. Pilot plant.	39	2800, (incl. capital grant)	80	60	0.12	20
Large-scale gasifier, ~30 MW						
• Belarus	14	360	80	40	0.034	12.5
• UK	23	1500	80	60	0.09	19

7.1.4 Case study in Belarus

A decentralised electricity production scheme by gasification of coppice wood fuel was evaluated for a hypothetical village in Belarus. The ECOP-model was used for the analysis. As mentioned earlier, the ECOP and RECAP model were compared by ETSU and outcomes were very similar. Contrary to RECAP, ECOP calculates the economic profitability of the global system, production and conversion are managed by one entity. For more information in ECOP we refer to Goor (1998b). [The pilot gasification modelled below is evaluated in the TCR-Gazel project and is proposed in Belgium for decentralised electricity production at peak demands. This implies a low total production at high electricity prices.]

For the Belarus reference scenario, plantation was mechanical with an adapted vegetable planter and harvest was with a local forage harvester. A yield of 12 t ha^{-1} was taken. This is somewhat higher than the potential yield recorded for Belarus (10.5 t per ha; Chapter 4) but this yield was used since 12 t is considered as a standard yield for well-developed SRC. Cost of local machinery was used if these data were available. If not a price ratio West/Belarus of 5 was used. Specialised machinery was quoted at import price.

The gasification system for electricity production was of 350 kW capacity. Its cost price was calculated from the ratio of the prospected cost of an 830 kW gasifier (data from IPEP: 16 500 EUR) and the cost of a gasifier of this capacity in Belgium: 388 375 EUR). The ratio of 23.5 obtained was then used to calculate the cost of a 350 kW gasifier in Belarus. This factor 23.5 difference in costs was considered very high since it may be expected that part of the gasifier components have to be imported. Therefore a safety factor of 3 was applied giving a plant cost of 33 100 EUR. With an availability of 75 % this type of gasifier can provide a village of 2400 people [average global energy consumption of 970 kWh per person per year (data from IPEP)] with electricity. The electricity buying and selling price was the industry price for electricity (0.034 EUR kWh^{-1}) since at the low price for the domestic consumption (0.0032 kW h^{-1}), the system is not profitable. More details can be found in Annex 3. The results for this base case scenario are presented in Table 33.

Even with the relatively high electricity price, the system is not economically viable. The IRR is positive but the required IRR is 10 % or more for the industry (between 5 and 10 for agriculture). When the plant capital cost proposed by IPEP is applied (expected to be 11 000 EUR for the 350 kW unit), the system IRR becomes 7.95 % and the required 10-15 % is almost reached

Table 33: Costs and economic viability of electricity production from SRC in Belarus for reference case

Variable	Value
SRC production, EUR odt^{-1}	22.35
SRC storage, EUR odt^{-1}	0.75
SRC transport, EUR odt^{-1}	0.08
SRC chipping, EUR odt^{-1}	0.00
NPV (global), EUR ha^{-1}	-100
NPV (ha^{-1}), EUR ha^{-1}	-431
IRR (global), %	4.86

The harvesting option has a limited impact on system profitability: manual harvesting results in an IRR of 1.8 %, whereas for harvest in stems (imported Swedish machinery), the IRR becomes negative.

On the other hand, the price of the cuttings has a considerable impact on the global system profitability. A cutting cost of 0.1 EUR results in an IRR of 4.4 %. At a cutting cost of 0.025 EUR (about one third of cost in reference scenario) the IRR becomes 15 %. If cuttings could be produced in Belarus, this might render the system more profitable the IRR becomes 20.11 % (see annex 3 for details). However, at domestic electricity price or European capital costs, even this system is uneconomic.

A yield decrease of 50 % (6 t ha^{-1}) rendered the IRR negative.

Comparison with the RECAP analysis can be done to some extent since in the case of RECAP production and conversion are considered separately. For the 150 kW gasifier (Annex 1, 3.4), the farmer only makes a good profit (IRR 19 %) when yield is 12 t ha^{-1} (cutting price = 0.045 EUR) and only marginally when yield is 6 t (IRR 11 %). It should be noted that in these circumstances the fuel wood selling price is 40 EUR per t, about 4 times higher than the value quoted for waste wood in Belarus. The plant owner only makes a profit when the electricity selling price is 0.047 EUR per kWe, about 25 % higher than the industry electricity price. Results from both models hence show that these conversion systems are only (marginally) profitable in optimal conditions.

7.2 *Economics of liquid biofuel production from annual crops*

As mentioned earlier, the economic modelling of the annual crops oil seed rape (OSR), winter wheat (WW) and sugar beet (SB) was done using the CRISP model (Crop Resource Integrated System Model), a model developed under RECOVER and compatible with RECAP.

7.2.1 Comparison of Belarus and Western European situations

The major differences between the Western European situation and Belarus outlined above for SRC also apply for annual crops (Table 34). Current and potential yields (Chapter 5) are lower in Belarus than in Western Europe.

Table 34: Important factors for modelling the economics of producing liquid biofuels from annual crops in Belarus and Western Europe

Factor	Belarus	Western Europe	Comment
Labour cost	0.3-1.6 EUR h^{-1}	6- 22 EUR h^{-1}	A factor of at least 10 lower in Belarus
Farm machinery cost (tractor)	17 kEUR	45 kEUR	A factor of 3 to 8 lower in Belarus, depending on the machine
Crop prices, EUR t^{-1}			
WW	160	110-140	Similar price for OSR for Western Europe and Belarus. Higher prices quoted in Belarus for WW and SB.
SB	60	38 (50 for sugar)	
OSR	166	165-185	
Annual land rent	0	225 EUR ha^{-1} upwards	At present , no opportunity cost for land in Belarus
Production grants	0	487 EUR ha^{-1} OSR 383 EUR ha^{-1} WW	Set aside grant for OSR Area payment for WW Presently no grants for Belarus
Conversion plant capital costs			No data available from Belarus. Recent advice suggests same equipment costs as W. Europe
By- product prices	May not be able to use if contamination levels high	Important contribution to reducing cost of biofuel produced.	No data from Belarus. Data for W. Europe from literature.
Market price for biofuels			Assumed that they will compete with mineral diesel.

7.2.2 Comparison of production cost of different annual crops in Belarus and Western Europe

Table 35 shows that the production cost per hectare is much lower in Belarus than in W. Europe. However, the yields achieved in Belarus are also much lower than in W. Europe. We have also assumed that the net margin required in Belarus is lower. It therefore turns out that the price of the feedstock for the conversion process will be similar in W. Europe and Belarus. For OSR this is achieved by claiming the set aside grant for industrial OSR.

The sensitivity analysis revealed that yield has an important impact on the net margin. Even for the lower yields recorded for Belarus, production is still profitable. Transport distance has a substantially smaller effect.
For the Western European case, OSR production is not profitable without the set aside payment for OSR. In Belarus, revenue from OSR and SB production is close to the land opportunity cost.
It is worth noting that the quantity of SB currently grown in Belarus is estimated by IPEP to be less than 400 ha. For OSR the estimate is about 5000 ha, and for WW 43 000 ha. This is small-scale production compared with the amounts required to fuel the large-scale biofuel conversion plant proposed.

Table 35: The production costs for large scale production units, actual yield in Europe and actual and potential yield in Belarus

CROP	**Cost of Production EUR ha^{-1}**				**Yield t ha^{-1}**	**Market price EUR t^{-1}**	**Net margin EUR ha^{-1}**	**Target net margin EUR ha^{-1}**	**Min. crop price§ EUR t^{-1}**
	Growth	Harvest	Store/ Transport	Total					
Oil seed rape									
W. Europe	508	188	41	738	3.2	165	-210	225	300**
Belarus	125	75	12	212	2.0	166	120	100	156
					2.7	166	206		
Sugar beet									
W. Europe	678	287	304	1269	66	38	1239	225	23
Belarus	309	81	97	487	25	25	137	100	24
					55	25	744		
Winter wheat									
W. Europe	413	107	92	612	7.5	110	212	225	112
Belarus	130	42	19	191	3.2	160	321	100	95

§ To achieve target net margin
** Industrial OSR is produced at the market price with the aid of the set aside grant in W. Europe

7.2.3 Conversion costs for biodiesel and bio-ethanol production

For the conversion plant, we assume that all the crops will be processed into liquid biofuels for use as transport fuel. Estimates of capital costs have been based on Western estimates. Almost all plants considered are large-scale and in case of SB we assume that the beet-end plant already exists. If this is the case in Belarus with currently only a small production area of SB is not clear.

Table 36 shows that the cost of producing liquid biofuels is in all cases substantially above the cost of mineral diesel, so that subsidies for conversion to biofuels are required in all cases.
The cost of labour in Belarus, and also the rate of return on capital in Belarus is lower than in W. Europe, making the cost of biofuel production lower (except for OSR), assuming the by-products can be sold on the world market.

Table 36: Costs linked with bio-diesel and bio-ethanol production in W. Europe and Belarus for different conversion scales.

Product	Feedstock cost EUR t^{-1}	By-product income EUR t^{-1}	Capital cost MEUR	Operating cost MEUR y^{-1}	Biofuel cost EUR t^{-1}*
Biodiesel (RME)		**Meal/*Glycerine***			
W. Europe, 30000 t y^{-1} RME	165	150/*675*	21.0	2.8	390
Belarus, 10000 t y^{-1} RME	166	191/*511*	12.4	1.3	390
Belarus, 2000 t y^{-1} RME	166	191/*511*	3.0	0.2	420
Bioethanol from SB		**Pulp/*Vinasses***			
W. Europe, 24000 t y^{-1}	25	95/*95*	18.0**	3.7	550
Belarus, 24000 t y^{-1}	25	95/*95*	18.0	2.6	430
Bioethanol from WW		**DDG**			
W. Europe, 24000 t y^{-1}	110	135	32.0	3.6	756
Belarus, 24000 t y^{-1}	107	135	32.0	2.7	575

* Minimum price for biofuel for which both producer and conversion plant operator meet their target rate of return

** Fermentation plant only- assuming that beet end processing and animal feed processing already exists.

The capital cost of new power plant for biofuel production in Belarus is most likely to be the same as that in W. Europe. The effects of reducing the capital cost in Belarus with a factor 2 reduces the RME, of bioethanol from SB and WW cost to respectively, 290, 380 and 505 EUR t^{-1}, still substantially above the fossil fuel prices (187 and 210 EUR t^{-1}). If the by-products cannot be sold in Belarus due to contamination levels, then the cost of biofuel production will increase by about 25 % for bioethanol and about 90 % for biodiesel.

7.2.4 Conclusions

All three annual crops considered can be grown successfully in Belarus. The farmers will make high profits on SB and WW at the quoted market prices. At the prices expected for fuel crops, the farmers can achieve a net margin of at least 100 EUR ha^{-1}. In Western Europe, OSR production is only profitable with price support.

Both in Belarus and Western Europe, liquid biofuels produced all require price incentives to compete with fossil fuels, even when revenue from by-products is accounted for.

The by-products of the conversion process make an important contribution to the economics of the scheme, especially for RME. The prices which could be achieved for these products in Belarus are uncertain, and there is a possibility that the by-products may be too contaminated to be used. In this case the cost of bioethanol production will increase by about 25 % and RME production by about 90 %.

7.3 *Extra costs linked with a contamination scenario*

Two types of costs may arise when dealing with a contamination scenario: a probabilistic cost, when having to compensate for the dose occurred, and a cost linked with the disposal of contaminated wastes.

A discussion on the issue of compensating people when doses are in excess of 1 mSv a^{-1} (dose limit to a member of the general public) goes beyond the scope of the project. For European countries an alfa-value ranging between 25000 and 250000 EUR per Sv is proposed.

An extra dose can be obtained during production of the energy crops, transport of the product, conversion, disposal and discharges from the stack. From Chapter 4 it could be concluded that the extra annual dose from cultivating SRC or annual crops is low and the dose from transport and atmospheric discharge is negligible.

For people working constantly in the vicinity of the ash collectors or at the ash deposit, radiation levels may exceed the 1 mSv a^{-1} limit but only when extreme conditions are considered [high contamination levels in wood: 3000 Bq kg^{-1}; 2000 hours at 50 cm from collectors (15 mSv a^{-1}) or 1 m from the deposit (20 mSv a^{-1})].

These people should be monitored or considered as radiation workers. Estimating connected costs goes beyond the scope of the present project.

During conversion, several by-products can be formed. The most important 'real' waste product is the ash that is left after gasification or combustion. In principle these ashes can be used as fertilisers in case of gasification or sole burning (no co-burning with coal or municipal waste). Ashes may also have to be improved before return to the field given their often-caustic character. In actual practice, ashes are however often dumped. The wastes from the other liquid biofuel conversion routes are often used as animal fodder. The ashes from the straw burning from OSR and WW undergo the same fate as the SRC-wood ash.

In case of a contamination scenario, waste and by-product management may be entirely different. Table 12 in Chapter 3 gives an overview of the amounts of waste or by-products produced during conversion, for the different energy crops considered. For OSR and winter wheat also the ash from straw burning is included. For a number of contamination scenarios (185, 555 and 1480 kBq m^{-2}) the contamination levels in the waste products were calculated. It followed from Table 12 that for WW and OSR only the ash from the straw burning should be considered as waste, the other waste products could still be used as animal fodder (with some considerations). Only at the highest soil contamination, the oil cake produced during OSR conversions and the pulps and vines from SB conversion should be discarded as wastes. For SRC two calculations were made: one with the average transfer factor recorded for the Swedish SRC fields and one for the TF recorded in Belarus. Based on the exemption limits for caesium in fuelwood and with the lowest level of Low-Level Waste (1 to 100 Bq g^{-1}) as criterion, ashes should not be regarded as wastes when the lower TFs (10^{-5} m^2 kg^{-1}) apply. With the TFs for SRC in Belarus, which are comparable to the TFs to deciduous and coniferous wood, even at the lower soil contamination level, all ashes should be considered as waste.

Since these crops are produced for energy generation, it is important to have an idea of the amounts of waste produced per amount of net energy generated. The net amount of energy generated for the different cultivation systems was taken from Goor *et al.* (1998a). We did not take the energy values recorded in Chapter 6 of this report since for OSR and WW the energy from the combustion of straw was not accounted for in the analysis. In case a certain product (e.g. the straw from WW) was considered as waste, its energy content was not incorporated in the net energy calculation. From Table 12, partially copied here (Table 37), it is clear that the amount of waste generated per net energy production is lowest for coppice or forestry. At the highest soil contamination, amount of waste per GJ is substantial for OSR and WW.

Table 37: Waste produced per net amount of energy generated (kg waste per GJ generated) for 3 contamination scenarios (kBq m^{-2}). For detailed information, see Table 12.

CROP	185	555	1480
Rape seed	2.4	2.4	26.2
Winter wheat	1.8	1.8	1.8
Sugar beet			95.8
SRC TF=10^{-5} m^2 kg^{-1} (Sweden)	0	0	0
TF=10^{-3} m^2 kg^{-1} (Belarus)	1.1	1.1	1.1
Forests	1.1	1.1	1.1

There is a cost associated with the waste products which have to be disposed off. According to Grebenkov (1997, personal communication) the prospected cost for disposal of contaminated ashes will mount to about 8 EUR m^{-3}. With an ash density of 0.6 kg L^{-1}, this will mount to 13 EUR t^{-1}. Waste disposal costs for low-level contaminated wastes are in the order of 50 EUR t^{-1} (Andersen K., Risoe, personal communication). Knowing the amount of waste generated per net energy generated (kg GJ^{-1}, Table 37) and the cost of waste (EUR t^{-1}), we can calculate the cost of the waste disposal per unit energy produced (EUR GJ^{-1}) (Table 38).

If the revenue from bioethanol (WW, SB) and biodiesel (OSR) are 210 and 190 EUR per t, respectively, and with the respective energy contents of 29 and 40 GJ t^{-1}, this comes down to 7.24 and 4.75 EUR GJ^{-1}, respectively. For Europe the revenue/cost for electricity is 0.045 EUR $kWhe^{-1}$ and 0.034 EUR $kWhe^{-1}$ for industrial consumption in Belarus (It is no use to do the calculations for the domestic electricity price since the low revenue: only 0.0032 EUR $kWhe^{-1}$ renders the system non-profitable under all scenarios). With an average energy efficiency of combustion and gasification units of 0.30 we can calculate back the economic value of one GJ wood-energy content, which is, respectively, 3.75 and 2.83 EUR GJ^{-1}.

Table 38: Costs for the amount waste generated (EUR GJ^{-1}) under different contamination scenarios (kBq m^{-2}) as described in Table 12 for a disposal cost of 13 and 50 EUR t^{-1} in Belarus and Western Europe, respectively. For SRC the situation with the highest TF was considered.

	Belarus			Western Europe		
CROP	***185***	***555***	***1480***	***185***	***555***	***1480***
Rape seed	0.031	0.031	0.341	0.12	0.12	1.31
Winter wheat	0.023	0.023	0.023	0.09	0.09	0.09
Sugar beet	0	0	1.25	0	0	4.79
SRC and Forest	0.014	0.014	0.014	0.055	0.055	0.055

It is clear from Table 12 that for WW and OSR, about 33 % of the energy produced come from, respectively, the bio-ethanol and bio-diesel and that the remaining energy comes from the other products. The straw may be burnt by which electricity is produced. For this electricity we have the same revenue as was mentioned just earlier for fuel wood. For the sake of simplicity we will also consider that the other waste products are burnt and not used for animal consumption. This means thus that for the revenue of the net energy output, 33 % will be rewarded at the price for bioethanol of biodiesel (7.24 and 4. EUR GJ^{-1}) and 67 rewarded at the electricity price (3.75 EUR GJ^{-1} for Europe and 2.83 EUR GJ^{-1} for Belarus). Now we can calculate how cost of the waste disposal per unit energy is related to the revenue per unit energy. This is presented in Table 39.

Table 39: Cost of waste disposal as percentage of revenue from energy production.

	Belarus			Western Europe		
CROP	***185***	***555***	***1480***	***185***	***555***	***1480***
Rape seed	0.91*	0.91	9.91	1.95§	1.95	21.34
Winter wheat	0.55*	0.55	0.55	1.47§	1.47	1.47
Sugar beet	0	0	17.2	0	0	66.15
SRC and Forest	0.5*	0.5	0.5	1.47§	1.47	1.47

For the electricity produced with burning from wood or straw and other waste products from OSR and WW: * industrial energy price in Belarus 0.034 EUR $kWhe^{-1}$: § European price 0.045 EUR $kWhe^{-1}$

It follows from Table 39 that only a small percentage of the revenue from energy production should be dedicated to the waste disposal in case of the wood biofuel pathway. It should also be remembered that the situation here described for SRC is for the case with the high TF obtained in Belarus. With the lower transfer factor recorded in Sweden, no waste is produced!
The amount of money, which should be envisaged for disposal, is in the order of 0.5 to 2 %. Except for scenarios with high surface deposition, the amounts of waste produced in the OSR and WW pathways become substantial: between 22 and 66 % for Western Europe and between 10 and 17 % for Belarus from the revenue goes to the provision of a suitable waste disposal.

However, as was concluded from Chapter 7.3, conversion to liquid biofuel is not economically viable without any price support. Since the disposal costs will most probably be allocated to the plant owner, his loss (or the subsidies required) will increase even more.

In case of the 30 MW gasifier for electricity in Belarus, working at 80 % availability, 3500 ha (yield of 12 t ha^{-1}) are harvested each year and converted to electricity which is sold at 0.034 EUR $kWhe^{-1}$. This results in an annual waste generation of 840 t. If this waste has to be disposed off at a disposal cost of 13 EUR per t, this comes down to 10 920 EUR per year. Since the NPV of the conversion plant owner is 2 547 000 ECU, the cost linked with the waste generated is about 0.5 % from the revenue, which is only a small percentage and this pathway will certainly remain profitable. For other economically viable conversion routes, the part of the disposal cost to the revenue was between 0.5 and 3 % and will hence not have a substantial impact on system viability. Calculated percentages are also in close agreement with the ones calculated from literature data as presented in Table 39.

8 Comprehensive evaluation

Under the RECOVER project we have aimed to assess the potential of growing Short Rotation Coppice (SRC) and three other bio-fuel crops, oil seed rape (OSR), winter wheat (WW) and sugar beet (SB) as alternative crops on contaminated arable land. The case of Belarus, the country most seriously contaminated as a result of the accident at the Chernobyl Nuclear Power Plant, and a Western European scenario were evaluated. Both radiological and radioecological consequences and general ecological and economic aspects of the implementation of these alternative options were considered. Table 40 gives an overview of the final assessment of the criteria considered for the different energy crops.

Overall, SRC is more appropriate as alternative land-use option than the bio-fuel crops studied, since the former energy route is economically and ecologically more sustainable.

On radio-ecological grounds there is not too much concern for none of the crops. Activity levels in the useable plant parts are generally low and the same holds for the waste products.

Broadly we may say that in light textured soils with a low radiocaesium interception potential (RIP) the TF to wood varies between 0.5 10^{-3} and 2 10^{-3} $m^2\ kg^{-1}$ and for soils with a medium to high RIP between 0.2 10^{-5} and 5 10^{-5} $m^2\ kg^{-1}$. Only about 0.01 % of the soil radiocaesium was transported to the above-ground plant parts, of which 40 % was immobilised in the wood and the rest returned by leaching-off by rain and litterfall.

Estimates for the radiocaesium concentration in the willow wood can only be given with a substantial uncertainty (as is the case for most crops). We were unable to derive transfer factor functions for predicting the radiocaesium content in willow wood based on soil characteristics. However, the K concentration in the soil solution affected the ^{137}Cs level in the wood to a large extent. Therefore, fertilisation of K-deficient soils will decrease the TF. Behaviour of caesium and K were not comparable in a SRC-ecosystem and hence we could not derive the Cs-behaviour from what is already known about K. No significant effect of variety and stand maturity on the TF was revealed, except for the rather short-term lysimeter trial. We found that for the first rotation cycle, TF decreased continuously on a loamy soil whereas for the sandy soil the TF increased following the year of cut-back and stabilised (or even decreased) after the 1st year of re-growth.

Comparison between the willows grown on the Belgian test sites and a 17 year-old-forest in Belarus, has shown that the net annual radiocaesium accumulation is about 35 times higher in the forest standing biomass than in coppice. Since, in addition, potential annual biomass increase is only 6 t ha^{-1} for forests and 12 t ha^{-1} for SRC, wood production on contaminated land seems more promising in a SRC system for these conditions than with traditional forestry, for the present example. However, when establishing forests on already contaminated land, the soil-to-wood TF is expected to be lower than in the scenario when the foliage intercepted part of the radiocaesium deposited. Since the potential yield expectations of SRC grown on a soil with low water reserve are 5 t ha^{-1} for Belarus and actual yields (nutrient limitations) are even lower, forestry is possibly may be a better land-use option than SRC on this type of soils (economic comparison not done). On soils with an adequate water reserve and nutrient status, SRC for energy production may be preferred to forestry.

In Belarus, the exemption limit for burning fuel wood is 740 Bq kg^{-1}. Limits for Low Level Waste (LLW) are between 1 and 100 Bq g^{-1}. If the TF to SRC wood applies for coppice grown on relatively fertile soil with a moderate to high radiocaesium fixation capacity (RIP), wood can be safely burnt and also the ashes can be disposed off without concern. In case the high SRC-TFs for low-RIP soils pertain (2 10^{-3} $m^2\ kg^{-1}$) which is potentially relevant for low fertile and low RIP soils (e.g. peaty and sandy soils), wood burning would only be permitted when willow is grown on a soil contaminated with <370 kBq m^{-2} ^{137}Cs. Under the limits presented above, ashes should be treated as LLW. Given that TFs for common forestry (2 10^{-3} $m^2\ kg^{-1}$) and for straw of winter wheat and oil seed rape (0.3 and 0.63 $m^2\ kg^{-1}$) are more or less comparable, considerations for burning wood or straw for energy are alike. At higher soil contamination levels, wood (straw) could be burnt in commercial electricity or heat plants but adequate exhaust filtering systems should be installed and appropriate ash-disposal should follow.

Table 40: Final assessment of criteria for the different energy crops considered.

Criteria		Coppice	Other crops
Radio-ecology	+	• Generally low TFs, except in situations with extremely light-textured soils of low RIP and low soil K • TF generally factor 10-1000 lower than for forests	• During conversion, activity goes mainly to by-products and wastes, bio-fuel almost contaminant-free • More information on TFs and relationship soil characteristics and TF
	-	• Levels in wood may be higher than the exemption limits for fuel-wood • No unique relationship found between soil characteristics and contamination level	• OSR and SB, generally higher TF than SRC • High TF to straw; content in straw may exceed exemption limits for fuel-wood
Dosimetry	+	• Not labour intensive	• No problems (> labour intensive than SRC but only for high contamination of concern)
	-	• When dealing with highly contaminated wood, dose in excess of 1 mSv a^{-1} may occur during conversion and at ash disposal site	• If straw is burnt and ashes have to be collected, doses in excess of 1 mSv a^{-1} may occur
Technico-agricultural feasibility	+	• Little-demanding; range of soils appropriate • Technically easy culture; common farm machinery may be used (some should be adapted)	• Known cultures: a lot of information on crop performance, crop requirements, farmers acquainted • All machinery available
	-	• Relatively new crop; less information on crop performance, new crop for farmer • Need for new machinery for higher efficiency • ~30 % yield loss expected on soils with low water reserve for continental climate (Belarus)	• 30 (WW) to 60 % (SB, OSR) yield loss expected on soils with low water holding capacity when going from sea climate (W. Europe) to a more continental climate (Belarus)
Ecological sustainability	+	• High energy efficiency (>6) • Reduction in CO_2 emissions with factor 11 and 25 compared to gas and coal burning • Low crop requirements, low mineral leaching, low emission of gases	
	-		• High fertiliser rates and pesticide use • Energy efficiency close to one. If by-products considered: 2-3. • Max. CO_2 reduction factor 1.5-3
Economic profitability	+	• Production side in Belarus: gain at wood-fuel price of at least 40 EUR t^{-1} and a yield comparable to W. Europe • Conversion in Belarus: at industrial tariffs, all heat schemes considered were potentially economic. Electricity schemes are only marginally profitable (industrial tariffs, high availability, plant manufactured in Belarus) • Wood contamination levels are generally so low that ashes can be disposed off without concern. In case ashes have to be considered as waste, extra cost is about 0.5-3 % of the revenue	• In Belarus the OSR producer can make reasonable profit if yield of 2 t ha^{-1} is reached • SB and WW production in W. Europe profitable if price for beet and wheat is at least 23 and 110 EUR t^{-1}, respectively • In case of contamination, generally disposal costs only 0.5-2 % of revenue
	-	• Decentralised small-scale electricity production in Belarus hardly viable. • Production side W. Europe only viable at high yield, high bio-fuel price (60 EUR t^{-1}) and without storage cost. If these optimal conditions do not apply, grants are needed • Conversion side in W. Europe: generally not profitable without price support	• If by-products cannot be sold (high contamination), cost of RME and bio-ethanol production increase with 100 and 20 %, respectively. • Production of OSR in W. Europe unprofitable without set-aside payment. • For conversion, a substantial subsidy is required both for W. Europe and Belarus • In case of severe contamination (1480 kBq m^{-2}), disposal costs may mount to 10 and 20 % for OSR in Belarus and W. Europe and 17 and 66 % for SB
Economic risk	+ -	• Lower risk than forestry since returns faster • Higher risk than annual crops	

TFs to the useable product (rape seed, wheat grains, beet root) for the other bio-fuel crops considered range between 0.08 10^{-3} and 0.5 10^{-3} m² kg^{-1} and the liquid bio-fuels are almost free from activity. Radiocaesium levels in the by-products are generally of no concern. In case of high deposition (~1000 kBq m^{-2}), Cs-levels in the oil cake from OSR (~2000 t ha^{-1}) and the pulp and vines from SB (~ 4000 t ha^{-1}), exceed the exemption level for use as animal fodder and for incineration and should, therefore, be disposed off. Since amounts to be disposed off are substantial, this involves a high disposal cost (up to 30 and 60 % of the revenue for OSR and SB, respectively). This waste could also be burnt resulting in a mass reduction of about 90 %.

In case of high contamination levels in the wood (3000 Bq kg^{-1}) (or straw or oil cake and pulp) doses at different locations in the combustion plant may exceed the acceptable level of 1 mSv a^{-1} for a member of the general public. The highest doses are at the fly-ash silo (16.4 and 3.5 mSv a^{-1} if at a distance of 0.5 or 5 m from the collector for 2000 h). Under such conditions, workers should be controlled (personal dosimeters). With appropriate work-rotation-schemes doses can most probably be brought down to less than 1 mSv a^{-1}, even in case of high(er) contamination levels. If ash of this highly contaminated biofuel is disposed of, dose at the disposal site may be as high as 20 mSv a^{-1} (2000 h at 1 m distance). Therefore, personnel dealing with the ash handling and working at the ash disposal site should be controlled.

Contributions from other possible radiation pathways (external exposure during culturing and transport), inhalation dose in the plant and to the general public following wood or liquid bio-fuel burning are negligible.

The potential yield of all four crops studied is about 10 % lower under the continental Belarus climate compared to yield estimates in Western Europe on a soil with adequate nutrient level and water holding capacity. On soils with low water reserves, potential yield decreases between 30 and 60 % in Belarus. Since yield is an important parameter controlling economic viability, appropriate yield levels are important.

Regarding the ecological sustainability of cultivating crops for energy production, the electricity or heat production routes have much better energy and carbon budgets than the liquid fuel routes. Compared with gas and coal fired power plants, energy requirements are respectively a factor 16 and 23 lower for the wood-fired power plants. CO_2 emissions from wood fuel burning are a factor 11 and 25 lower than for gas and coal burning. The overall energy efficiency of the SRC-route ranges between 10 and 30. For the liquid bio-fuels, the energy efficiency is close to one. Reduction of CO_2 emissions when using bio-fuels as transport fuel is maximally about a factor 1.5 to 3.
Further, mineral and pesticide emissions are high for OSR, WW and SB cultivation and erosion risk may be pronounced (SB). For SRC, pesticide and fertiliser use is limited and leaching to water table is insignificant.

The economic sustainability of cultivation and conversion of energy crops was evaluated for Western Europe and Belarus. Important differences in system parameters between both regions are that labour costs are a factor of at least ten lower in Belarus, no grants are available in Belarus, farm machinery prices are lower in Belarus by up to a factor of five, domestic heat and electricity prices are much lower in Belarus and finally, boilers for heat production are cheaper by a factor of three to five in Belarus.

In Western Europe, electricity production from SRC is currently only viable with both production incentives and electricity price support at the conversion side.

The SRC production cost in Belarus is potentially lower than in Western Europe, due to the lower labour and machinery costs. However, to maintain this advantage, the yield of SRC in Belarus must approach that in Western Europe. A yield decrease by 50 % renders the production side unprofitable. This implies that SRC cultivation for energy production on sandy soils under the Belarus continental climate conditions will hardly be profitable since the potential yield is only about 5 t ha^{-1}. Since about 60 % of the soils in Belarus are of a sandy nature, only a small percentage of soils are apt for SRC cultivation. These soils should better be reforested or used for perennial grasses or with other crops adapted to low water and nutrient conditions.

Another important parameter for SRC-production profitability is the price of the bio-fuel delivered at the plant. To make production profitable in Belarus, about 40 EUR t^{-1} is required (in W. Europe even higher). At this bio-fuel price, which is a factor 4 higher than the amount paid for waste wood as biofuel, a profit can be made both at the production and the conversion site. The harvesting technique also affects the profitability at the production site. Harvesting in chips is preferred to harvesting in sticks and separate chipping. Transport distance only affects production profitability to a limited extent.

For conversion, the most significant parameter was the price that could be achieved for the electricity or heat. In Belarus, domestic tariffs (0.0032 EUR kWhe^{-1} for electricity and 0.001 EUR kWh^{-1} for heat) are much lower than industrial tariffs (0.034 EUR kWhe^{-1} and 0.026 EUR kWh^{-1}), and none of the schemes considered were economic for domestic electricity or heat production.

For industrial tariffs, the heat schemes considered were all economic, under condition that they are run at a higher availability (80 %) than the quoted 16 %, which is for seasonal heat production. Heat schemes already exist in Belarus, using forest residues as fuel. Our work has shown that SRC could be used as the fuel paying 40 EUR odt^{-1} to the producer for the delivered chipped fuel. Even when the costs of the conversion system are increased by a factor 3-4 compared to the costs quoted for Belarus, these conversion routes may still be viable.

For electricity production in Belarus, results are more speculative, since no conversion plant currently exists. In our original calculations we assumed a lower capital cost of conversion plant in Belarus, which led to large and small scale schemes being marginally profitable where industrial electricity tariffs were achieved and availability was high. However, if part of the power plant components have to be imported, capital cost may become more likely 50 % -100 % of that in Western Europe. Using these figures, electricity production is not economic in Belarus without price support for the electricity or capital grants for plant construction.

Only a small percentage of the revenue from energy production is to be dedicated to the waste disposal in case of the wood bio-fuel pathway. This will not render the profitable systems uneconomic.

Regarding the economics for the other three crops, OSR, WW and SB can be grown successfully in Belarus if the potential yields (appropriate soil conditions) are attained. In Western Europe, OSR production is only profitable with price support. Both in Belarus and Western Europe, the cost of liquid bio-fuels is about 3 to 4 times the cost of fossil fuels and hence price subsidy is needed to compete with fossil fuels. It is therefore highly improbable that these crops can be advocated as potential alternative crops for a contamination scenario since the production-conversion schemes are even in non-contamination conditions un-profitable. A nuclear accident will certainly affect the market structure, but how this will potentially change the profitability of the bio-fuel cycles is beyond the scope of this project.

Conclusions

We may hence conclude that the energy production from SRC is a potentially ecologically and economically sustainable land-use option in situation of contamination or not, but that the feasibility of the biofuel chain depends on a number of factors: legislation, crop performance and economics, social acceptability and market.

First of all, in case of considerable contamination and high soil-to-wood transfer factors, plant owners should be allowed to burn biomass, which is contaminated, above the acceptable level for burning fuel-wood. This would mean that exemption limits for domestic and industrial use should be different. Efficient filtering systems should be adopted, disposal should be adequate and conversion plant workers and waste disposal people should be controlled. On the other hand, if the conversion routes are found profitable, disposal costs generally only account for a few percent of the revenue.

The economic viability of the systems should be thoroughly calculated through for the prevailing conditions. For Belarus, profitability at the production side largely depends on yield and price of the delivered bio-fuel. Since most of the territory consists of sandy soil, for which yield estimates are too low to make production profitable (if no irrigation), conversion systems can only be implanted in a restricted area. However, the soils not apt for SRC could be reforested. Certainly under conditions of restricted land-use in case of substantial contamination, SRC and traditional forestry seem complementary land-use options. Moreover, larger scale heat conversion systems which can be supplied with various wood products and residues, seem the most profitable and revenue may be considerable. For smaller scale units, e.g. for decentralised heat production, conditions should be optimal to attain break-even. Electricity routes are generally unprofitable, unless they are exploited at almost maximum availability and when plant building costs are the ones quoted for Belarus.

An important disadvantage of growing a perennial crop is the higher risk for the farmer in comparison with cultivation of an annual crop. High investment costs for perennial crops can hardly abide the lack of flexibility and amount of uncertainty. After having invested in SRC, farmers can only change to other crops at high costs. Perennials cannot be included in rotation-set-aside schemes and large-scale-practical experience is limited. Compared to normal forestry, revenues arise from the 3rd year onwards in SRC and only after 20-80 year for forests. If the forested area is sufficiently large, in the longer run, returns will come regularly. Only in the short-medium long term perspective revenues from forestry are small.

When advocating or installing a new culture and connected conversion route, an important aspect to consider is also the infrastructure needed and the availability of a market to sell the product (heat and electricity). The viability of the system will also depend on the macroeconomics [price evolution of fossil fuels, electricity and heat (as already partly investigated), of transport costs, etc] and on socio-political perception. In case of a severe contamination, public perception and boundary economic conditions will certainly be affected. Assessment of the impact of macroeconomics and socio-political aspects, though extremely important, is, however, outside the scope of this project.

Perspectives

Production of energy from SRC scores rather good on radio-ecological and general ecological grounds.

We were not able to put forward transfer functions which would predict the radiocaesium levels in the coppice wood based on soil characteristics. Generally, levels in wood will be of no concern and radiation exposure during cultivation and conversion will be far below the dose limits. In case caesium levels are higher than the exemption levels for fuel wood, just simple measures will be adequate to guarantee a low radiation exposure. This would hence mean that the SRC bio-fuel route would not be hampered by radiological concerns.

With the present price scales in Western Europe, large-scale use of biomass crops for energy would require financial support, by production incentives or electricity or heat price support. This implies that production of energy from biomass is not likely to be competitive in the short and medium term and will depend on government incentives. We might also argue that fossil fuels are too cheap and should be taxed to take into account their harm to the environment.

For Belarus, the SRC route for energy production may be viable. Cost of the cuttings, yield, and price paid for the bio-fuel delivered affect the viability at production side mostly. Since it is rather improbable that soils will be irrigated on large scale, SRC cultivation on sandy soil in Belarus should generally not be recommended. Conversion pathways for heat are viable but a case-by-case investigation is needed. Conversion to electricity is much more expensive. Liquid bio-fuel pathways should best not be advocated as alternative land-use, since production and conversion grants are required, to make them profitable. For economically viable conversion routes, cost of the waste disposal is just a few percent of the revenue.

In a contamination scenario, when food crop production is banned or when there are psychological constraints to cultivate food crops, the land can be turned into value by the cultivation of bio-energy crops, without a real radiological concern. Heat and electricity routs (e.g. SRC, forestry) are preferred to liquid bio-fuel routes. Government incentives, political willingness, availability of a market and social acceptance are however indispensable.

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11 Contributions by the partners

The *radioecological aspects* of the study were dealt with by SCK•CEN, U.LUND and RISOE. SCK•CEN was responsible for the lysimeter studies in Belgium and for a detailed radiocaesium flux study in a pilot gasification unit running on willow wood. U.LUND was responsible for site selection and sampling of coppice stands in Sweden. Sample analysis and interpretation of result were done in collaboration with SCK•CEN. U.LUND was also responsible for the study of the fate of radionuclides for different biofuels and for the dosimetrical aspects. RISOE was in charge of the co-ordination of work done in Belarus. IPEP co-ordinated the coppice trials in Belarus and was assisted by the RIR, the PSRER and BSU. Analysis of biomass production data was done by UCL and SCK•CEN interpreted the radiocaesium soil-to-plant transfer data.

Dosimetry of coppice cultivation and processing were dealt with by U.LUND and RISOE (dose during processing).

UCL dealt with the *technico-agricultural* aspects.

Economic feasibility of coppice cultivation and conversion was considered by UCL on farmer scale. ETSU, sub-contracted by SCK•CEN, modelled the energy and carbon balance and economic cost-benefit of the cultivation of coppice and other energy crops. All data for Belarus were collected by IPEP. UCL and ETSU collected Belgian and UK data, respectively.

SCK-CEN co-ordinated the project.

Annex 1

Economic modelling of short rotation coppice

Table of contents

1 The RECAP model

The Renewable Energy Crop Analysis Programme, RECAP, was designed in the UK to model the costs and benefits to producers and conversion plant operators of individual biomass schemes. It models perennial crops, such as SRC or energy grasses, where there are multiple harvests and the economic viability of the scheme needs to be assessed over the lifetime of the project.

RECAP calculates the economics of a biomass-to-energy system in terms of the Internal Rate of Return (IRR) and Net Present Value (NPV) to both crop producer and energy producer, and net margin for crop producer. The system represents this process in three major stages, each with its own screen:

1. Production; this models all the costs of production of the energy crop, from establishment of the plantation, through the various agricultural activities required to grow the crop and harvest it. A total cost per hectare is calculated for each year from establishment. Revenue is also calculated for the assumed yield and crop price, and the farmer's cash flow is thus calculated.
2. Interface; this models the rate at which stocks of energy crop rise and fall as it is produced and consumed; it monitors the resulting loss of dry matter and moisture content as the wood is stored, and takes account of the rate of harvesting by the farmer and use by the energy producer. It also calculates the requirement for secondary feedstock to make up any shortfall in supply or any excessively we supply.
3. Conversion; this models the conversion of the wood to heat and power in the conversion plant. It calculates the energy producer's costs in terms of plant setup and running expenses and feedstock costs, and his revenue from the heat and power sold.

There are additional screens in the system to define the variables which influence the economics. There is also a "key variables" screen which displays values of major input variables and shows the results (NPV, IRR for crop and energy producers and net margin for crop producer).

Detailed description of RECAP is beyond the scope of this report. However, a number of clarifying observations are needed for understanding its operation

- IRR is only calculated when there is a favourable NPV and an initial investment; no relevant figure is otherwise possible.
- A value of "opportunity cost" for the land can be input; this gives a measure of the relative desirability of alternative land uses.
- The program makes no assumption at all about the agro-climatic conditions which may be driving crop yield. A single value of yield is input to the program by the user, who is assumed to have taken this into account.

In this report RECAP has been used to model both SRC fuelled schemes and forest residue fuelled schemes.

2 Short rotation coppice systems modelled

A range of possible biomass to energy systems have been modelled for SRC under the RECOVER project.These cover the different scales of system and the different technologies which we think might be applicable in Belarus. The systems modelled for Belarus come under two types.

- Systems based on existing use of biomass for heat in Belarus. These uses of biomass for heat are a medium scale heating boiler, a small scale gasifier for heating and a 'cluster' of heating boilers. The first two systems are based on data for heating units obtained from our partners in Belarus. The third is a system which we feel might be economic in Belarus, and uses data on Belarus boilers
- Systems for electricity production. Biomass is not currently used for electricity production in Belarus, and much of the equipment used in Western Europe for electricity production is still at the pilot stage. However, potentially biomass could make a contribution to electricty production in Belarus. Three systems were therefore modelled, the 8 MW demonstration scale gasifier, an estimate for a 30 MW commercial scale gasifier and a small scale 150 kW gasifier. These systems were based on Western European cost data, but in the sensitivity analysis the effect of reducing the cost due to the equipment becoming commercial and being manufactured in Belarus were considered.

Part of ETSU's remit was to compare the Western European situation with that in Belarus. One immediate difference is that in Western Europe the SRC schemes often generate electricity. In Belarus no electricity is generated from wood, which is used exclusively for heat production. The interest in electricity generation in W.Europe is often political in origin, with Governments aiming to replace some of their generation capacity with Renewable sources. For example in the UK the introduction of the NFFO scheme, offering higher prices for electricity generated from renewables, has concentrated effort on electricity generating schemes. For medium scale schemes, at about 8 MWe, the W. European scheme is therefore a gasification scheme for electricity production. For small scale systems, we have modelled the Belgian gasifier which is for electricity production. However, we have also modelled a small scale gasifier used for heat production in the UK, to try to obtain a direct comparison between the West and Belarus.

2.1 Sources of information

2.1.1 Information on Belarus

Information on Belarus was from the RISO- IPEP reports from the RECOVER project. This report gave information collected from Belarus on the economics of production of energy from wood waste.

2.1.1.1 Reliability/ relevance of information

In general, we used the Belarus data collected by RISO-IPEP where possible. However, data related only to woody waste, since no SRC is currently grown in Belarus. Advice on the production of SRC in Belarus was obtained from ECOP-UCL, as detailed under the individual studies.

The conversion data supplied applied to heat production only, and was given in terms of ranges of values, which made it difficult to enter into RECAP in the detail required. Some inconsistencies were also found in the data, and we used our judgement to obtain what we felt was a reasonable overall picture. Estimates for the cost of electricity production plant were based on Western information, adjusted for the assumption that 70 % of the equipment could be manufactured in Belarus.

2.1.2 Information from Western Europe

The UK data for production and conversion comes from the best available UK data, which has been verified and entered into RECAP.

Information on SRC production in Belgium was obtained from ECOP-UCL. As part of the RECOVER project, ECOP-UCL has undertaken a detailed sensitivity analysis of SRC production and conversion using a small scale gasifier under development in Belgium. It was therefore important that the RECAP and ECOP-UCL models were compatible in their assessment of SRC economics. A detailed intercomparison of the two models was undertaken by ETSU.0 The intercomparison showed that the two models were performing the calculations in a similar way, and used similar assumptions for the costs and depreciation of machinery, and labour costs and times for operations. There are some differences in the production scenarios between the UK and Belgium, which are discussed in the individual case studies.

2.2 *Important system parameters for West Europe/ Belarus comparison*

2.2.1 Yield/ cost of cuttings

All the systems modelled used willow as the SRC material. Willow has been chosen as the preferred SRC material in Western Europe, and there is considerable experience of growing willow, usually on a three or four year cutting cycle. New varieties of willow are being produced all the time in W.Europe, to improve pest and disease resistance and to increase yield. At the current time cost per cutting range from 0.045 EUR in Sweden to 0.12 EUR in the UK. The density of planting also varies, from about 10000 ha^{-1} in the UK up to 18000 ha^{-1} in Sweden. Cost of establishment is therefore very variable.

In general, willow has been established successfully, and a yield of 12 odt^{-1} ha^{-1} y is considered reasonable for the crop after the first two rotations. Plantations have an expected lifetime of 15-25 years.

For Belarus it is not clear what the source of cuttings would be. For the purposes of this study we have assumed that in Belarus cuttings will be bought from Sweden at 0.045 EUR per cutting, and that establishment will be successful, with only a 5 % replacement required. The work on the agronomy of willow in the RECOVER project demonstrates that potentially willow SRC could be grown successfully in Belarus. However, water limited yields calculated for Belarus are considerably lower than the yields achieved in Western Europe, being about 5 to 11 odt ha^{-1} y, and actual yields (3.4 odt^{-1} ha^{-1} y) achieved in the trial plots are even lower .

2.2.2 Labour costs/mechanisation

The labour costs quoted for Belarus are a factor of at least 10 less than those for W.Europe. This reduces the labour costs to the extent that mechanisation is often not cost effective. This is reflected in the way more operations are carried out manually according to the Belarus data, and in the more simple production and conversion equipment which requires more manual operation. Typically in W.Europe, a plant is designed to be as automatic as possible, leading to high capital costs but low running costs. These designs may not be appropriate to Belarus, and so as far as possible we have used Belarus estimates of plant costs and labour.

2.2.3 Cost of machinery

Machinery produced in Belarus is considerably cheaper than that in W.Europe, sometimes by up to a factor of five. This reduces costs of schemes, provided specialist equipment does not have to be imported for the scheme. For this reason we have assumed that schemes in Belarus will be based on existing Belarus technology for heat schemes, and mainly manufactured in Belarus for electricity schemes.

2.2.4 Grants

No grants are actually available in Belarus. For comparison all the base cases have been run without production grants. However, the electricity prices quoted in the W.Europe situations include the price support available for renewable energy in all cases.

2.3 *Sensitivity analysis for SRC for energy systems*

In addition to the differences between West Europe and Belarus noted above, some parameters are of particular concern within the SRC as an energy source system, as being an important component of the total cost, but not well known at this time. These are the costs of harvesting, transport and storage on the production side and the cost of capital equipment for commercial plant on the conversion side.

2.3.1 Harvesting and storage

There are currently two methods of harvesting under consideration
- cut and chip harvesting, where the SRC is chipped at the same time as harvesting
- stick harvesting, where, the SRC is harvested and stored in stick form (for drying) and is chipped at a later date.

Cut and chip harvesting is cheaper, but the chips then require careful management to avoid deterioration before use. Sticks are easier to store, but the separate chipping operation can be very costly. There is no allowance for storage in any of these scenarios. This is considered to be acceptable for stick harvesting, but an underestimate for cut and chip harvesting.

2.3.2 Transport

The RECAP model includes a simple algorithm for calculation of transport costs. The same algorithm is used in the CRISP model. This should only be seen as a rough estimate of transport costs. In the work done for RECOVER, we have used the best guess of the vehicle which will be used for transport, and the average distance we believe the material will be transported. In particular, this may not be applicable to the types of roads found in Belarus.

2.3.3 Capital equipment for conversion plant

The information available in the UK and Belgium for conversion plant to electricity is based on pilot or demonstration plant. It is estimated that the cost of commercial plant may be up to three times less than for the pilot plant. For the large scale gasifier, a case has been specifically set up for a commercial scale, 30 MW, plant using best cost estimates.

For the Belarus power plant, the figures for the heat production plant have been derived as far as possible from the data provided from Belarus. Our comparison with UK heating plant shows that the cost in Belarus is estimated to be about 5 times less than in the UK. However, it is difficult to be sure of the comparisons because of the different elements included in each of the estimates. For electricity production the costs are based on the UK and Belarus plant data, and adjusted to Belarus costs, assuming 70 % can be built in Belarus. Plant capital costs are therefore varied by up to a factor of 5 in the sensitivity analysis.

3 Individual cases modelled

Conversion technology	Belarus	UK	Belgium
HEAT			
Large scale, 28 MW(t)	X		
Medium scale, 3 MW(t)	X		
Small scale, 330 kW(t)	X	X	
ELECTRICITY			
Large scale, 30 MW(e)	X	X	
Medium scale, 8 MW(e)		X	X
Small scale, 150 kW(e)	X		X

3.1 *Belarus boiler cluster for heat, large scale 28 MW(t)*

3.1.1 Data Sources

The IPEP/ RISO data is used for production, combined with advice from ECOP-UCL. The boiler data is based on the IPEP general data on Belarus boilers.

3.1.2 Assumptions

At this scale the use of harvesting and planting equipment will be optimised, and if separate chipping is the choice, then a large chipper with a throughput of 10 odt hr^{-1} will be employed. The transport distances remain small, because we have assumed a cluster of boilers each of which will be supplied by the nearest sources of SRC.

3.1.3 Key input variables

Variable	Base case value	Most realistic values
Area of energy crop	5000 ha	
Energy crop price	10.2 EUR odt^{-1}	40 EUR odt^{-1}
Grants included	No	
Crop suppliers discount rate	5 %	
Plant capacity	7.5 odt h^{-1}	
Electricity price	N/A	
Heat price	0.026 EUR kwh^{-1}	
Energy producers discount rate	10 %	
Whole shoot harvesting	1.8 h ha^{-1}	4.32
Separate chipping	0.1 h odt^{-1}	0.5
Average transport distance	40 km	
Dry matter loss in storage	15 %	
Capital cost of project	3.6 MEUR	

3.1.4 Key output parameters

Variable	Base case	Most realistic case
Crop suppliers net margin	-61.8 EUR ha^{-1}	38 EUR ha^{-1}
crop suppliers NPV	-1164 EUR ha^{-1}	145 EUR ha^{-1}
Crop suppliers IRR	Unprofitable	6.5 %
Energy producers NPV	33 MEUR	20 MEUR
Energy producers IRR	84 %	59 %

3.1.5 Sensitivity analysis

This shows the effect of varying chosen parameters on the key output parameters. In this case the fuel price, harvesting costs and capital costs of the conversion plant were considered.

- **Fuel price** . The quoted fuel price is so low that the producer could never make a profit, yet the conversion plant operator is making a large profit. This is likely to be because fuel prices quoted do not include chipping and transport. The fuel price was increased to 40 EUR odt^{-1}. At this price both producer and conversion plant operator make a reasonable profit, showing that such a scheme is viable, provided the production costs can be kept this low, and the capital costs from Belarus are achievable.
  In fact, assuming the production work rates can be achieved and the capital costs are achievable, then the price of the wood fuel of 70 EUR odt^{-1}, will lead to a profitable scheme for both producer and conversion plant operator.
- **Harvesting costs-** The rates of work for both harvester and chipper quoted are very high. The rates quoted in the RECOVER report for harvesting and in the IPEP data for chipping are therefore inserted. The production net margins and NPV remain positive, but are now very low.
- **Capital costs of conversion-** The lowest values in the range for equipment and building costs have been used. If the top end of the range are used then the IRR is reduced to 33 %, which is still a good rate of return.

Variable	Base	1	2	3
Fuel price, EUR odt^{-1}	**10.2**	**40**	**70**	
Crop suppliers net margin		195		
Crop suppliers IRR, %	unprofitable	20	32	
Energy producers IRR, %	84	59	30	
Harvesting time, h ha^{-1} **Chipping time h ha^{-1}** (with 40ECU odt^{-1} price)	**1.8** **3.6**	**4.32** **18**		
Crop suppliers net margin	195	38		
Crop suppliers IRR, %	20	6.5		
Energy producers IRR, %	59	59		
Capital cost, MEUR (with 40 EUR odt^{-1} price)	**3.6***	**6.2***	**10.8***	**14.4***
Energy producers NPV	20	16	11	7
Energy producers IRR, %	59	33	22	16

*: 3.6 and 6, lowest and highest quoted price in IPEP-document, respectively. Two other prices are lowest quoted price times 3 and 4.

3.1.6 Conclusions

This is a viable set up for heat production in Belarus. There is considerable profit in the conversion side, so that the price paid for the fuel can be higher than normal for Belarus. This may be necessary to make production profitable, since the production side costs could be underestimated, and the sensitivity analysis shows that this could turn the production to a loss.

3.2 *Belarus boiler for heat, medium scale, 3 MW(t)*

3.2.1 Data sources

The IPEP/RISO data is used together with advice from ECOP-UCL for production. The boiler data is used on the actual Belarus data described in the IPEP report.

3.2.2 Assumptions

For production, the equipment is assumed to be fully utilised, although this is a smaller scale of operation at 120 ha^{-1}. The average transport distance was 6 km. The dataset for the boiler was incomplete, and was combined with general data on boilers from Belarus to estimate all the information required. The boiler was for heat production only and its efficiency was assumed to be about 70 %. The availability was very low, about 16 %, suggesting it was run on a seasonal basis only. The labour requirements stated are very high, leading to a substantial cost even at the low rates for Belarus. The capital and operating costs are taken form the general boiler costs in the IPEP data. The lifetime of the plant was assumed to be 25 years, and the plantation lifetime was matched to this.

3.2.3 Key input variables

Variable	Base case value	Best case values
Area of energy crop	120	600
Energy crop price	10.2 EUR odt^{-1}	40 EUR odt^{-1}
Grants included	No	
Crop suppliers discount rate	5 %	
Plant capacity	0.9 odt h^{-1}	
Electricity price	N/A	
Heat price	0.026 EUR kwh	
Energy producers discount rate	10 %	
Whole shoot harvesting	4.32 h ha^{-1}	
Separate chipping	0.5h odt^{-1}	
Average transport distance	6 km	14 km
Dry matter loss in storage	10 %	10%
Capital cost of project	0.38 MEUR	
Plant availability	16 %	80%

3.2.4 Key output parameters

Variable	Base case	Best case
Crop suppliers net margin, EUR ha^{-1}	-210	59
crop suppliers NPV, EUR ha^{-1}	-3113	433
Crop suppliers IRR, %	Unprofitable	9.1
Energy producers NPV, MEUR	0.078	1.5
Energy producers IRR, %	12.3	42

3.2.5 Sensitivity analysis

- **Fuel price-** The fuel price was increased to 40 EUR odt^{-1}. This made the net margin and NPV for the producer positive, but only just. The conversion plant operator is now making a loss.

- **Harvesting/ chipping costs-** As in the gasifier case, the profitability for the producer can be increased by reducing the harvesting cost, either by cut and chip harvesting, or by reducing the chipping cost. However, at best this increases the Net margin to 209 EUR ha^{-1}and with a lower fuel price the production still makes a loss.
- **Capital cost-** The IPEP data give a range of values for the capital cost of the equipment. The costs used are at the bottom end of the range suggested by IPEP.
- **Availability-** Very low availabilities are quoted for the system, reflecting seasonal usage we assume. We feel that such a low availability is strange both from the view of the heating season for Belarus, and for the return on capital investment. If the availability were 80 % then the conversion operation becomes much more profitable.

Variable	Base	1	2
Fuel price, EUR odt^{-1}	**10.2**	**40**	
Crop suppliers net margin	-210	63	
Crop suppliers IRR, %	unprofitable	9.4	
Energy producers IRR, %	12.3	unprofitable	
Bundle harvesting+chipping	**Yes**		
Forage harvesting (with 40 EUR odt^{-1} price)		**Yes**	
Crop suppliers net margin, EUR ha^{-1}	63	209	
Crop suppliers IRR, %	9.4	21	
Energy producers IRR, %	Unprofitable	unprofitable	
Availability, % (at 40 EUR odt^{-1} fuel price)	**16**	**80**	
Crop suppliers net margin, EUR ha^{-1}	63	60	
Crop suppliers IRR, %	9.4	9.1	
Energy producers IRR, %	Unprofitable	42	
Cost of capital equipment, MEUR (80 % availability)	**0.38**	**1.14**	**1.52**
	IPEP estimate	(IPEP x 3)	(IPEP x 4)
Energy producerss NPV, MEUR	1.5	0.9	0.3
Energy producers IRR, %	42	19	13

3.2.6 Conclusions

In conclusion, the base case as presented from Belarus assumes a seasonal operation of a plant, a low capital investment and a low fuel price. We assume this corresponds to a fairly simple conversion plant, with considerable requirement for manual operation, using wood obtained as residues or low grade wood from existing forests. Our model shows that if wood can be obtained at 10.2 EUR odt^{-1}, then there is a modest profit in producing heat using this equipment. However, if the wood is grown as SRC, then the production operation is not profitable, even if the chipping costs are set against the conversion plant operator and a yield of 12 odt ha^{-1} is assumed.

The only way to make the operation profitable is to increase the price for the wood. We have tried 40 EUR odt^{-1}, which is a low fuel price in W. Europe, and leads to a very small profit for the producer. Payment of 40 EUR odt^{-1}, however, leads to a loss for the conversion plant operator. This can be resolved by increasing the availability of the plant.

Two profitable scenarios therefore emerge
- seasonal operation with cheap fuel (current Belarus situation)
- all year round operation paying higher fuel price of at least 40 EUR odt^{-1}.

3.3 *Belarus gasifier for heat, small scale, 350 kW(t)*

3.3.1 Data sources

RISO-IPEP data were used where possible. No SRC is currently grown in Belarus, and no information was therefore available on production methods. However, information on general farm machinery in Belarus is available, and this was used in the run, together with advice from UCL on specialised machinery which may be appropriate for Belarus.

Some data were also given by IPEP for a small scale gasifier. However, the data were so far outside our experience that we did not feel it was useful to include them all. For example, labour rates of 2 man-days GJ^{-1} and consumables of 200 EUR GJ^{-1} were far in excess of anything which we would expect. We speculate that labour costs may include time for chipping, stacking and loading, which have been included in other parts of the RECAP model. However, we believe that the consumables cost must be an error.

3.3.2 Assumptions

For production, a more manual system has been assumed for the small scale of SRC production required here, together with a no input system for fertilizers and use of herbicides only at establishment. The standard yield of 12 odt ha^{-1} y is used in the base case, but we believe this is unrealistic for the small scale operation, and the effect of reducing the yield to 3.4 odt ha^{-1} y in line with estimates for Belarus has been investigated in the sensitivity analysis.
For the gasifier, we have used the capital cost and discount stated in the data, together with the input of 0.1 odt hr^{-1}. We have assumed that the plant will be manned continuously while in operation, but that consumables, excluding fuel, will be 0.1 EUR t^{-1}. Assuming a 70 % efficiency for the boiler, we have a rating, for woodchips, of 350 kW(t).

3.3.3 Key input variables

Variable	Base case value	Best case values
Area of energy crop	12 ha	
Energy crop price	10.2 EUR odt^{-1}	40 EUR odt^{-1}
Grants included	No	
Crop suppliers discount rate	5 %	
Plant capacity	0.1 odt h^{-1}	
Electricity price	N/A	
Heat price	0.026 EUR kwh^{-1}	
Energy producers discount rate	10 %	
Whole shoot harvesting	4.32 h ha^{-1}	forage harvesting
Separate chipping	0.5 h odt^{-1}	
Average transport distance	1 km	1 km
Dry matter loss in storage	5 %	10 %
Capital cost of project	0.02 MEUR	
Plant availability	16 %	

3.3.4 Key output parameters

Variable	Base case	Best case
Crop suppliers net margin, EUR ha^{-1}	-187	237
crop suppliers NPV, EUR ha^{-1}	-2816	2774
Crop suppliers IRR, %	Unprofitable	22
Energy producers NPV, MEUR	0.043	0.014
Energy producers IRR, %	33	20

3.3.5 Sensitivity analysis

This shows the effect of varying chosen parameters on the key output parameters. In this case the fuel price, harvesting costs and yield were considered.

Variable	Base	1	2
Fuel price, EUR odt^{-1}	**10.2**	**40**	
Crop suppliers net margin, EUR ha^{-1}	-184	90	
Crop suppliers IRR, %	unprofitable	12	
Energy producers IRR, %	33	20	
Bundle harvesting+chipping	**Yes**		
Forage harvesting (with 40 EUR odt^{-1} price)		**Yes**	
Crop suppliers net margin, EUR ha^{-1}	107	237	
Crop suppliers IRR, %	13	22	
Energy producers IRR, %	20	20	
Yield, odt^{-1} ha^{-1} y (at 40 EUR odt^{-1} fuel price)	**12**	**3.4**	**3.4+forage harvesting**
Crop suppliers net margin, EUR ha^{-1}	90	-6	36
Crop suppliers IRR, %	12	unprofitable	6.3
Energy producers IRR, %	20	20	20
Availability, % (at 40 EUR odt^{-1} fuel price)	**16**	**30**	**60**
Crop suppliers net margin, EUR ha^{-1}	107	106	106
Crop suppliers IRR, %	13	13	13
Energy producers IRR, %	20	39	72
Cost of capital equipment, MEUR	**0.02** IPEP estimate	**0.115** (100 % W. European cost)	**0.057** (50 % W. European cost)
Energy producerss NPV, MEUR	0.014	-0.09	-0.024
Energy producers IRR, %	20	n/a	2

The analysis shows that at 40 EUR odt^{-1}, both production and conversion are profitable for a small seasonal gasifier producing heat. The best case is when forage harvesting is used to reduce harvesting costs, with the assumption that the chips will not need to be stored for long, and that existing storage can be utilised. This scenario assumes that 12 odt ha^{-1} y^{-1} can be achieved. For the more realistic case of 3.4 odt ha^{-1} y^{-1}, the scheme can still be marginally viable, but only if the harvesting costs are minimised. This is in fact the only cost which can be reasonabley reduced, since the establishment, production, storage and transport costs are all very low in this scheme.

If a higher availability is assumed, the energy producers return is greatly increased. However, the system is still not profitable at the domestic heat prices quoted for Belarus. Small increases in the capital cost renders the system uneconomic.

3.3.6 Conclusion

This type of scheme can be of use to a local group, for a complex of houses, or equivalent, where the fuel can be sourced locally and perhaps the conversion unit run by the consumers, to minimise the costs of chipping fuel and maintenance of the gasifier.

3.4 Belarus gasifier for electricity, small scale, 150 kW

3.4.1 Data sources

The same data sources were used for production as for the small scale gasifier for heat.
For the conversion data, there are no gasification units for electricity production currently in Belarus. The data used are therfore based on the Belgian demonstration unit. Information on this unit was received from ECOP-UCL. Since this unit is intended to be used for domestic consumers, the domestic rate for electricity in Belarus was used. This was obtained from the RISO/IPEP data and is 0.0032 EUR kWh^{-1}.

3.4.2 Assumptions

The same production assumptions are made as for the small scale heat gasifier. For conversion, we started off using the same parameters as for the Belgian scenario, except that the electricity price and fuel prices are thoses for Belarus. Conversion makes a large loss. We then tried adjusting the scenario to Belarus conditions

- Reducing the capital cost by a factor of 5, to account for production of the equipment in Belarus
- Increasing the availability to 80 %, so that the unit is producing base load electricity, rather than peak load only.
- Increasing the electricity price by a factor of 10 to industrial levels, to simulate the maximum price which might be achievable in Belarus.

Even reducing the capital cost and fuel price do not make the scheme profitable. Looking at the conversion spreadsheet shows why this is so. At 40 EUR odt^{-1} delivered fuel cost, the fuel price is equal to the electricity revenue, even using the industrial tariff. The 40 EUR odt^{-1} cannot be reduced, as producers are only just making their target IRR of 5 %, and the assumptions about harvesting, storage and transport are already optimistic. Therefore the only way to make this scheme profitable is to obtain a higher electricity price in Belarus. This will depend on the political will.
If we assume the capital cost is 20 % of that for the Belgian pilot plant and that an availability of 80 % can be achieved then an electricity price of just under 0.05 EUR kwh^{-1} must be obtained to achieve the target IRR of 10 % for the conversion plant operator.

3.4.3 Key input variables

Variable	Base case value	Best case values
Area of energy crop	250	70
Energy crop price	40	40 EUR odt^{-1}
Grants included	No	
Crop suppliers discount rate	5%	
Plant capacity	0.1 odt h^{-1}	
Electricity price	0.0032	0.047
Heat price	N/A	
Energy producers discount rate	10 %	
Whole shoot harvesting	forage harvesting	forage harvesting
Separate chipping		
Average transport distance	9 km	5 km
Dry matter loss in storage	15 %	
Capital cost of project	0.04 MEUR	
Plant availability	80 %	
Yield of biomass, odt ha^{-1}	3.4	12

3.4.4 Key output parameters

Variable	Base case	Best case
Crop suppliers net margin, EUR ha^{-1}	10	170
crop suppliers NPV, EUR ha^{-1}	-178	1749
Crop suppliers IRR, %	2	19
Energy producers NPV, MEUR	-0.3	-0.001
Energy producers IRR, %	unprofitable	9.9

3.4.5 Sensitivity analysis

Variable	Base	1	2	3
Electricity price, EUR kWh^{-1}	**0.0032**	**0.034**	**0.047**	**0.06**
Crop supplier net margin, EUR ha^{-1}	10	10	10	10
Crop suppliers IRR, %	2	2	2	2
Energy producers IRR, %	unprofitable	unprofitable	9.9	34
Cost of capital equipment, MEUR (at 0.034 EUR kWh^{-1} electricity price)	**0.04**	**0.02**	**0.01**	
Crop suppliers net margin, EUR ha^{-1}	10	10	10	
Crop suppliers IRR, %	2	2	2	
Energy producers IRR, %	not profitable	not profitable	not profitable	
Yield, odt^{-1} ha^{-1} y (at 0.034 EUR kWh^{-1} electricity and 40 EUR odt^{-1} fuel price)	**3.4**	**6**	**12**	
Crop suppliers net margin, EUR ha^{-1}	10	67	170	
Crop suppliers IRR, %	2	11	19	
Energy producers IRR, %	Unprofitable	unprofitable		
Yield, odt^{-1} ha^{-1} y (at 0.034 EUR kWh^{-1} electricty and 20 EUR odt^{-1} fuel price)	**3.4**	**6**	**12**	
Crop suppliers net margin, EUR ha^{-1}	-34	-11	52	
Crop suppliers IRR, %	Na	na	9	

- **Electricity price.** This is the determining factor in the profitablility of the conversion system. In the Belarussian case the domestic, and even industrial tariffs obtained are much lower than the peak load tariff obtained in Belgium. The electricity price must be at least 0.05 EUR kWh^{-1} for the scheme to break even.
- **Capital cost.** The system is relatively insensitive to capital cost reductions. This is because the annual net margin is negative for the Belarus electricity prices.
- **Yield.** If 12 odt ha^{-1} can be achieved, the producer can make a good profit. This is because the base parameters in this case are the lower cost option of forage harvesting and a fuel price of 40 EUR odt^{-1}. For a yields lower than 6 odt ha^{-1} the system becomes un-profitable.

3.4.6 Conclusion

This system will only be profitable in Belarus if an electricity price of 0.05 EUR KWh^{-1} can be achieved, even with all other parameters optimal.

3.5 Belarus gasifier for electricity, large scale, 30 MW

3.5.1 Data sources

For the production, the same basic data was used as for all the Belarus runs. For the conversion, the base data was that projected for the UK 30 MW commercial gasifier.

3.5.2 Assumptions

This is assumed to be an efficient large scale operation, achieving high work rates for harvesting and chipping, and 12 odt ha^{-1}yields. A transport distance of about 80 km is assumed. The delivered fuel price is set at 40 EUR odt^{-1}

The base data for the conversion plant is based on the predictions for UK commercial gasification plant at the 30 MW scale. It is assumed that 70 % of the plant can be made in Belarus, and overall the plant can be built for 0.3 of the cost of a plant in the UK. The same levels of staffing for operation asre assumed.

The electricity tariff achieved is assumed to be the Belarus industrial rate of 0.034 EUR kWh^{-1}.

3.5.3 Key input variables

Variable	Base case value
Area of energy crop, ha^{-1}	11000
Energy crop price, EUR odt^{-1}	40
Grants included	no
Crop suppliers discount rate, %	5 %
Plant capacity, odt h^{-1}	18 odt h^{-1}
Electricity price, EUR KWh^{-1}	0.034
Heat price, EUR kWh^{-1}	N/A
Energy producers discount rate, %	10 %
Whole shoot harvesting, h ha^{-1}	1.8 h ha^{-1}
Separate chipping, h odt^{-1}	0.1h odt^{-1}
Average transport distance, km	85 km
Dry matter loss in storage , %	5 %
Capital cost of project, MEUR	14 MEUR
Plant availability, %	80 %

3.5.4 Key output parameters

Variable	Base case
Crop suppliers net margin, EUR ha^{-1}	192
crop suppliers NPV, EUR ha^{-1}	2013
Crop suppliers IRR, %	21
Energy producers NPV, MEUR	2.6
Energy producers IRR, %	12.5

3.5.5 Sensitivity analysis

This shows the effect of varying chosen parameters on the key output parameters. In this case the capital cost of the conversion plant, the electricity price and the fuel costs were considered.

- **Electricity price.**The scheme is only profitable is the industrial electricity price is achieved
- **Capital cost of conversion equipment.** We have assumed for the base case that the plant will cost about 0.3 of the cost in the UK. In fact, this is close to the break even point of 14 MEUR. Increasing the capital cost renders the system uneconomic.
- **Fuel price.** Reducing the fuel price to 28 EUR odt^{-1}, which is the price calculated for residues, makes the conversion scheme more profitable, but this is not sufficient to allow production of electricity for the domestic market.

Variable	Base	1	2
Electricity price, EUR kWh^{-1}	**0.034**	**0.0032**	**0.0032** (fuel price 28 EUR odt^{-1}
Crop supplier net margin, EUR ha^{-1}	192	192	N/A
Crop suppliers IRR, %	21	21	N/A
Energy producers IRR, %	12.5	unprofitable	unprofitable
Cost of capital equipment, MEUR	**14**	**45** (cost in W. Europe)	**23** (1/2 of cost in W. Europe)
Crop suppliers net margin, EUR ha^{-1}	192	19	192
Crop suppliers IRR, %	21	12	21
Energy producers IRR, %	10	Not profitable	4.9
Yield, odt ha^{-1} (fuel price 40 ECU odt^{-1})	**3.4**	**6**	**12**
Crop suppliers net margin, EUR ha^{-1}	-13	49	192
Crop suppliers IRR, %	n/a	8.4	21
Yield, odt/ha (fuel price 20 EUR odt^{-1})	**3.4**	**6**	**12**
Crop suppliers net margin, EUR ha^{-1}	-64	-41	12
Crop suppliers IRR, %	n/a	n/a	3
Fuel price. EUR odt^{-1}	**40**	**28**	**28** (electricity price 0.0032 EUR KWh^{-1})
Crop suppliers net margin, EUR ha^{-1}	192	N/A	N/A
Crop suppliers IRR, %	21	N/A	N/A
Energy producers IRR, %	12.5	22.3	unprofitable

3.5.6 Conclusion

If gasification equipment can be built and installed in Belarus for the cost estimated, then it could supply electricity profitable to the industrial market.

3.6 UK gasifier for heat, small scale, 380 kW

3.6.1 Data sources

The production data is taken from the standard RECAP UK production runs. The conversion data is based on small scale heating schemes in the UK.

3.6.2 Assumptions

For production,
- Cuttings cost 0.12 EUR each
- harvesting is by forage harvester
- Storage is on field
- Yield is 12 odt ha^{-1}
- local transport only for fuel

For conversion
- conversion efficiency is 80 %
- capital cost is 115 kEUR
- plant operates automatically, requiring minimum repairs and maintenance

3.6.3 Key input variables

Variable	Base case value	Higher fuel price
Area of energy crop, ha^{-1}	62	
Energy crop price, EUR odt^{-1}	50	69
Grants included	No	
Crop suppliers discount rate, %	10	
Plant capacity, odt h^{-1}	0.1	
Electricity price, EUR KWh^{-1}		
Heat price, EUR kWh^{-1}	0.03	
Energy producers discount rate, %	20	
Whole shoot harvesting, h ha^{-1}	forage harvesting	
Separate chipping, h odt^{-1}		
Average transport distance, km	2 km	
Dry matter loss in storage , %	15%	
Capital cost of project, MEUR	0.115 MEUR	
Plant availability, %	80%	

3.6.4 Key output parameters

Variable	Base case	Higher fuel price
Crop suppliers net margin, EUR ha^{-1}	196	375
crop suppliers NPV, EUR ha^{-1}	126	1301
Crop suppliers IRR, %	10	16
Energy producers NPV, MEUR	0.011	-0.014
Energy producers IRR, %	22	12

3.6.5 Sensitivity analysis

No formal sensitivity analysis was done, as this case was done simply as a comparison with the Belarus gasifier. However, we can see that at the base case both enrgy crop producer and conversion plant operator are just meeting their investment criteria.

In fact, in the UK it is unlikely that farmers would produce SRC for this net margin, since the opportunity cost for land in the UK is estimated to be about 225 EUR ha^{-1}. (This small scale gasifier in fact runs on forest residues.) If the fuel price is set at the more realistic price of 69E UR odt^{-1} delivered chipped fuel, then the energy producers IRR falls to about 12%.

3.6.6 Conclusion

This type of small scale heating installation is viable in the UK, but margins are not large. They are most likely to succeed in situations where the production and conversion operations are run together, for example where an institution uses wood supplied from its own land to fire its own boiler, or when a farmer co-operative producing the fuel also runs the conversion facility.

3.7 UK gasifier for electricity, medium scale, 8 MW

3.7.1 Data sources

Production data were based on the standard data used for UK in RECAP. We have also looked at the recent trend towards stick harvesting and separate chipping. Costs of cuttings are based on UK sourced cuttings, but the effects of importing the cheaper Swedish cuttings was also considered. Conversion data were based on costs of a pilot gasification plant. The technology employed in such a pilot plant is not optimised for the 8 MW scale, and so we have also considered in a separate run an estimate of the costs associated with a 30 MW commercial plant based on the same technology.

3.7.2 Assumptions

Production
- Yield of 12 odt ha^{-1} y
- Average transport distance 44 km
- No fertilization
- Spraying after harvest

  Base case
  - Forage harvesting
  - Cuttings cost 0.12 EUR each
  - Cutting density 10000 ha^{-1}
  - Storage loss is 10 %
  - No grants included

  Most likely case
  - Stick harvesting and separate chipping
  - Cuttings cost 0.045 EUR each
  - Cutting density is 15000 ha^{-1}
  - Storage loss is 3 %
  - Include production grants

Conversion
- For base case best estimate of capital cost is 39 MEUR
- For most likely include capital grant , to reduce capital cost to 23 MEUR.
- Fuel price is 60 EUR odt^{-1}
- Electricity price is 0.12 EUR kWh^{-1}

3.7.3 Key input variables

Variable	Base Case	Most likely
Area of energy crop, ha^{-1}	5000	5000
Energy crop price, EUR odt^{-1}	60	60
Grants included	no	yes
Crop suppliers discount rate, %	8	8
Plant capacity, odt h^{-1}	8	8
Electricity price, EUR KWh^{-1}	0.12	0.12
Heat price, EUR kWh^{-1}	N/A	N/A
Energy producers discount rate, %	15	15
Whole shoot harvesting, h ha^{-1}	forage harvesting	1.8
Separate chipping, h odt^{-1}		0.1
Average transport distance, km	44	44
Dry matter loss in storage , %	10	3
Capital cost of project, MEUR	39	23
Plant availability, %	80	80

3.7.4 Key output parameters

Variable	Base case	Most likely
Crop suppliers net margin, EUR ha^{-1}	237	421
crop suppliers NPV, EUR ha^{-1}	863	3886
Crop suppliers IRR, %	12	not calculated
Energy producers NPV, MEUR	-11.2	5.9
Energy producers IRR, %	9.5	20

3.7.5 Sensitivity analysis

Variable	Base	1	2	3
Establishment cost, EUR ha^{-1} 10000 ha^{-1} at 0.12 EUR cutting 15000 ha^{-1} at 0.045 EURcutting	2088	1475		
Crop supplier net margin, EUR ha^{-1}	237	264		
Crop suppliers IRR, %	12	16		
Energy producers IRR, %	9.5	9.5		
Harvesting	**base (forage)**	**stick**	**Stick, 3% loss**	
Crop supplier net margin, EUR ha^{-1}	237	223	275	
Crop suppliers IRR, %	12	11.5	13	
Energy producers IRR, %	9.5	9.5	9.5	
Transport distance,km	**base (44)**	**23**	**89**	
Crop supplier net margin, EUR ha^{-1}	237	243	224	
Crop suppliers IRR, %	12	12.2	11.6	
Energy producers IRR, %	9.5	9.5	9.5	
Cost of capital equipment, MEUR	**39**	**24**	**14**	**12***
Crop suppliers net margin, EUR ha^{-1}	237	237	237	237
Crop suppliers IRR, %	12	12	12	12
Energy producers NPV, MEUR	-11.2	5.9	17.6	-16
Energy producers IRR, %	9.5	19	34	not profitable
Grants	**none**	**capital**	**Production**	
Crop suppliers net margin, EUR ha^{-1}	237	237	385	
Crop suppliers IRR, %	12	12	54	
Energy producers IRR, %	9.5	19	9.5	

*at 0.045 EUR kWh-1 electricity prive

The sensitivity analysis shows that, for production, the method of establishment, harvesting and transport distance all have a significant, but not overwhelming effect on the cost of producing the biomass, and that biomass production should yield about the opportunity cost for the land, under the given assumptions for production (e.g. high fuel price). In the UK case this means that it is unlikely that farmers will plant SRC unless grants are available, both to increase the net margin they achieve on the crop, and to reduce the perceived risk of establishing the crop. The most likely scenario for the UK therefore includes production grants, for establishment and for growing the crop on set aside land.

For conversion, the capital cost of the plant and the price achieved for the electricity are all important. Under the present electricity support scheme in the UK, the pilot plant costs still mean the project achieves a low rate of return. Including a capital grant ensures that the target rate of return is met. If the cost of the plant are reduced to the projected cost of commercial plant, then the plant is very profitable, but only if electricity price support is retained. If the electricity price drops to the standard UK price then the plant is not profitable.

3.7.6 Conclusion

Under current best practice for SRC production, the crop will achieve a net margin comparable to the opportunity cost in the UK, and will therefore require subsidies to encourage farmers to grow it. At the 8 MW scale, the gasification plant is viable with a capital grant and electricity price support.

3.8 UK gasifier for electricity, large scale, 30 MW

3.8.1 Data sources

Production data has been taken for the standard UK case from RECAP. Conversion data is projected commercial costs for such a plant.

3.8.2 Assumptions

Production: The same assumptions are made for the base case as for the 8 MW gasifier, except that the transport distance will be greater, average 89 km, because a much larger area of SRC is required to fuel the plant.

Conversion: Capital costs are set assuming this is a commercial plant, which has been replicated 30 times. Projected capital costs for such a plant are 1500 EUR kwh^{-1} Therefore, costs for conversion are considerably lower both since the plant is not a one off and since the scale of operation is optimal for the technology. If this were to be a truely commercial plant, no subsidies or grants would be required. This is therefore run as the base case.

3.8.3 Key input variables

Variable	Base Case	Most likely
Area of energy crop, ha^{-1}	12000	12000
Energy crop price, EUR odt^{-1}	60	60
Grants included	No	Yes
Crop suppliers discount rate, %	8	8
Plant capacity, odt h^{-1}	8	8
Electricity price, EUR kWh^{-1}	0.045	0.09
Heat price, EUR kWh^{-1}	N/A	N/A
Energy producers discount rate, %	15	15
Whole shoot harvesting, h ha^{-1}	forage harvesting	forage harvesting
Separate chipping, h odt^{-1}		
Average transport distance, km	89	89
Dry matter loss in storage , %	10	10
Capital cost of project, MEUR	45	45
Plant availability, %	80	80
Conversion plant efficiency,%	39	39

3.8.4 Key output parameters

Variable	Base case	Most likely
Crop suppliers net margin, EUR ha^{-1}	226	374
crop suppliers NPV, EUR ha^{-1}	770	3407
Crop suppliers IRR, %	12	54
Energy producers NPV, MEUR	-45	11.9
Energy producers IRR, %	not calculated	19

3.8.5 Sensitivity analysis

Variable	**Base**	**1**	**2**	**3**
Electricity price, EUR kWh^{-1}	**0.045 (base)**	**0.09**	**0.12**	
Crop supplier net margin, EUR ha^{-1}	226	226	226	
Crop suppliers IRR, %	12	12	12	
Energy producers NPV,MECU	-45	12	50	
Energy producers IRR, %	not profitable	19	30	
Storage loss	**10**	**5**	**15**	
Crop suppliers net margin, EUR ha^{-1}	226	264	190	
Crop suppliers IRR, %	12	13	10	
Energy producers IRR, %	not profitable	not profitable	not profitable	
Fuel Price, EUR odt^{-1}	**40 (base)**	**20**	**10**	
Crop supplier net margin, EUR ha^{-1}	226	-12	-125	
Crop suppliers IRR, %	12	n/a	n/a	
Energy producers NPV,MEUR	-45	-0.12	-0.11	
Energy producers IRR, %	not profitable	2	3	
Fuel Price, EUR odt^{-1}	**60**	**40**	**20**	**10**
(with production grants and electricity price of 0.09 EUR kWh^{-1})	374	199	24	-64
Crop supplier net margin, EUR ha^{-1}	54	46	32	n/a
Crop suppliers IRR, %	12	26	39	47
Energy producers NPV,MEUR	19	23	27	29
Energy producers IRR, %				

- **Electricity price-** We can see from the sensitivity analysis that the fuel cost cannot be reduced below 60 EUR odt^{-1} with present production practices. The capital costs of this plant are also set at what we feel will be the costs for commercial gasification plant at this scale. Therefore, the electricity price achieved must be at least 0.09 EUR kWh^{-1} for the system to be profitable. NB. Electricity price is not very sensitive to reduction in fuel price in this analysis.

3.8.6 Conclusion

This system still requires support in terms of production grants and price support for electricity. However, the level of price support for the electricity can be reduced to 0.09 EUR kWh^{-1} and the plant will remain profitable.

3.9 *Belgian gasifier for electricity, small scale, 150 kW*

3.9.1 Data sources

Production and conversion data is from Belgian data supplied.

3.9.2 Assumptions

3.9.2.1 Production

An intercomparison of the production side of the UK model RECAP and the Belgian spreadsheet for SRC production was carried out This showed that, in general, the two models were in agreement, and that similar values had been used for the machinery involved.
For the production runs in Belgium, the standard RECAP machinery table has therefore been used, but the Belgian data supplied for the time, materials and practices involved in SRC production has been extracted from the Belgian spreadsheets and used in the RECAP runs. The main differences in the production data between Belgium and UK are

- the cost of cuttings is lower in Belgium, at 0.046 EUR cutting. However, the stocking rate is much greater than in the Uk, at 18000 ha^{-1}. Overall the establishment cost for Belgium is 1871 EUR ha^{-1}, compared with 2000 EUR ha^{-1} in the UK.
- the harvesting is assumed to take place by forage harvester, and more quickly in Belgium than in the UK, at a rate of 1.6 h ha^{-1}, rather than 4.68 h ha^{-1} in the UK.
- There is fertilization at establishment.
- There is assumed to be no beeting up, i.e. repalacement of cuttings which have died.
- No grants are included
- Transport is assumed to be local only, since the amount of SRC required is 10ha.
- No allowance is made for storage, which will either be on field or in existing facilities.

3.9.2.2 Conversion

- The conversion unit is a 150 kW gasifier for electricity production
- The capacity of the unit is 0.1odt h^{-1}
- The capital cost , excluding connection and civil engineering but including 15 % profit, is 168000 EUR.
- The civil engineering cost is about 20000 EUR, including 15 % profit
- The construction time is short, at 3 months

- The unit operates automatically, and only requires preparation of wood and maintenance.
- If chipping is done at the unit this will take 0.5 h odt^{-1}. (This is excluded from the base run which includes cut and chip harvesting)
- Transport is estimated to be 30 journeys of 1 h each. (This is more pessimistic than the base run, where 12 tt transporter is used)
- Mainteneance of gasifier is by farm hand, and is about 40 h y^{-1}
- Maintenance of motor is by contract, and costs about 0.0075 EUR kwh^{-1}
- Only a small amount of waste is generated, and this is not included.
- The life of the installation is about 20 years.
- The conversion efficiency to electricity is 26.3 %. The heat generated is used for drying the wood chips.
- An attractive electricity tariff is achieved by using the unit for peak load only, with an availability estimated at 11%. The tariff is 0.107 EUR kwh^{-1} plus 0.025 EUR kwh^{-1} renewables premium.

3.9.3 Key input variables

Variable	Base Case
Area of energy crop, ha	10
Energy crop price, EUR odt^{-1}	58
Grants included	no
Crop suppliers discount rate, %	5
Plant capacity, odt h^{-1}	0.1
Electricity price, EUR kWh^{-1}	0.132
Heat price, EUR kWh^{-1}	N/A
Energy producers discount rate, %	15
Whole shoot harvesting, h ha^{-1}	forage harvesting
Separate chipping, h odt^{-1}	
Average transport distance, km	6
Dry matter loss in storage , %	10
Capital cost of project, MEUR	0.168
Plant availability, %	12

3.9.4 Key output parameters

Variable	Base case
Crop suppliers net margin, EUR ha^{-1}	312
crop suppliers NPV, EUR ha^{-1}	3019
Crop suppliers IRR, %	16
Energy producers NPV, MEUR	-0.14
Energy producers IRR, %	not calculated

3.9.5 Sensitivity analysis

Variable	**Base**	**1**	**2**
Harvesting	**Forage**	**stick chipping 0.5h odt^{-1}**	**stick chipping 0.2h odt^{-1}**
Crop supplier net margin, EUR ha^{-1}	312	-84	156
Crop suppliers IRR, %	16	not profitable	10
Energy producers NPV, MEUR	-0.14	-0.14	-0.14
Energy producers IRR, %	not profitable	not profitable	not profitable
Transport	**12tonne**	**5 tonne**	
Crop suppliers net margin, EUR ha^{-1}	312	260	
Crop suppliers IRR, %	16	15	
Energy producers IRR, %	not profitable	not profitable	
Fuel price EUR odt^{-1}	**58**	**40**	**10**
Crop suppliers net margin, EUR ha^{-1}	312	156	-97
Crop suppliers IRR, %	16	10	not profitable
Energy producers NPV, MEUR	-0.14	-0.13	-0.11
Energy producers IRR, %	not profitable	0.3	3
Capital cost, MEUR	**0.168**	**0.084**	**0.06**
Crop suppliers net margin, EUR ha^{-1}	312	312	312
Crop suppliers IRR, %	16	16	16
Energy producers NPV, MEUR	-0.14	-0.04	-0.007
Energy producers IRR, %	not profitable	6	13
Availability, %	**12**	**80**	
Crop suppliers net margin, EUR ha^{-1}	312	304	
Crop suppliers IRR, %	16	16	
Energy producers NPV, MEUR	-0.14	0.19	
Energy producers IRR, %	not profitable	30	

For the base case, the crop supplier achieves an IRR of 16 %. This is without grants, and is due to the low harvesting cost using a forage harvester, combined with a zero storage cost and low transport cost. It is therefore the most optimistic scenario. It is more likely that for short local journeys a smaller transporter will be used. For chips, a larger storage cost is likely to be incurred, or if the harvesting is in sticks, then storage could be zero, but a separate chipping operation is required.
The analysis was therefore done for stick harvesting including separate chipping, and transport using a 5 tonne transporter. The data for chipping times and transport times came from the Belgian conversion data.

- Inclusion of chipping as a separate operation greatly increases the harvesting costs for the chipping time of 0.5 h/tonne given. This makes the production operation unprofitable. The result is very sensitive to changes in the chipping time. If the time is reduced to 0.2 h/tonne, then an IRR of 10% is achieved.
- For transport, the cost increases from 128 EUR ha^{-1} to 203 EUR ha^{-1} for the smaller transporter. This does not have such an impact on the profitability as the harvesting.
- For conversion, the operation is not profitable, even with the high electricity prices achieved. The two parameters which were tested for sensitivity here were the capital cost and the price of the fuel. We thought that the fuel price was realistic for delivered and chipped wood, and indeed even reducing the fuel price down to 10 EUR odt^{-1} did not make the conversion operation profitable.
- The capital cost had to be reduced by a factor of three to make the scheme achieve an IRR close to the target.
- The third way of making the operation more profitable is to increase the availability. If an availability of 80% is achieved, then the conversion becomes profitable. However, it is unclear that these premium electricity prices can be achieved for a 80% availability.

3.9.6 Conclusion

This system is unlikely to be profitable for the conversion plant operator, unless a high tariff can be secured for longer than the 1000 hours operating time quoted. On the production side, the operation is profitable with the best estimates of harvesting, storage and transport. However, margins are still low and it is likely that if the opportunity costs of land in Belgium are taken into account, farmers will not plant SRC unless some form of production grant is also available.

Annex 2

Economic modelling of annual biofuel crops: oil seed rape, winter wheat and sugar beet

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1 The CRISP model

The Crop Resource Integrated System Package, CRISP, was developed as part of the RECOVER project to model the costs and benefits to producers and conversion plant operators of individual biomass schemes using annual crops as the feedstock. The CRISP model is based on the RECAP model for perennial crops described in Annex 1. CRISP, however, has been developed to consider the income from by-products of the liquid biofuels conversion processes, to deal with production on an annual cycle and to include information on the machinery and techniques associated with production of annual energy crops.

The model is in three interrelated parts.
1. Crop supplier's economics, modelling his income and expenditure streams to calculate critical financial factors for his operation.
2. Conversion plant operator's economics, modelling his income and expenditure schemes as for the crop supplier.
3. An interface between the two, modelling the price paid to the supplier by the operator for the crop, the quantity supplied, phasing of supply and consequent crop storage and decay.

The input values are used to calculate the following major output parameters.
- Crop suppliers net margin
- Crop suppliers NPV
- Crop suppliers IRR
- Conversion plant operators NPV
- Conversion plant operators IRR

The data interface with the user is through 6 main screens. Three of these are the production, interface and conversion screens described in Annex 1. There are also screens showing information on the production machinery, and on the labour charges. Finally, there is a summary screen of the 'Key Variable' showing the major input variables and the output parameters.

A detailed description of the CRISP package is not at the order here. However, it is worth making a few observations about the model.
- All costs up to the point of delivery to the power plant, i.e. including storage and transport of the feedstock, are counted against the crop supplier.
- The programme makes no assumptions about the agro-climatic conditions which may affect yield. Yield is entered as a single figure by the user.
- Most operations on the production side are calculated per hectare. However, the primary input for harvesting and chipping is hours per tonne. Harvesting costs will therefore increase with yield by default.
- IRR is only calculated where there is an initial investment and a favourable NPV. Otherwise no relevant figure is possible.

2 Annual crop systems modelled

A range of annual energy crops were modelled using CRISP to compare their economics with that of SRC and forest residues. The crops chosen were Oil Seed Rape, (OSR), Sugar Beet, (SB) and Winter Wheat, (WW).

These crops :
- are already grown in Belarus and have a high potential yield in the Belarussian climate on suitable soils
- can be converted to biofuels in straightforward processes which are already demonstrated.

On the production side the advantage of these crops is that they are well known to farmers, and so there should be no difficulty in their cultivation. On the conversion side, the crops would be converted to liquid biofuels. For OSR this involves esterification to produce RME, and for SB and WW this involves fermentation to produce bioethanol. Both these processes are well known and technically straightforward. The liquid biofuels produced could be used as transport fuel or for power generation. A particular advantage of liquid biofuel is that it is easily transported from the conversion plant to where it is required.

For RECOVER we agreed to look at large and small scale production of RME, and large scale production of bioethanol. Only large scale production of bioethanol was considered because previous studies have shown that this scale is required for the continuous extraction and fermentation processes. Since we wanted to compare the Western situation with that in Belarus, production and conversion of all three crops under W.European and Belarrusian conditions was therefore modelled.

2.1 Sources of information

2.1.1 Information for Belarus

Information about annual crops in Belarus was provided by IPEP for the RECOVER project.

The data from IPEP was generally good for production. Information was provided for the machinery used in Belarus, and for the cultivation operations for Belarus. We had some difficulties with individual parameters, and with interpreting the techniques used in Belarus in some cases, but in general the production in Belarus was successfully modelled.

IPEP provided no data for conversion for Belarus. They said that no liquid biofuels were currently produced and so no data could be collected. For RME data from the TACIS programme on conversion of OSR to RME in Belarus were used (GOPA, 1996)). These data gave estimates of the cost of RME production in Belarus, based on investigations in Belarus. Details of how these data were applied are given in the RME section. For boiethanol no data were received for either SB or WW. We therefore assumed that the same techniques would be used as in W.Europe. Latest advice from SCK was that the costs of building new conversion plant in Belarus would be similar to those in W. Europe. We used this as our base assumption, but applied labour rates for Belarus.

Some data for the price of the feedstocks, biofuels and by-products of conversion were provided by IPEP and GOPA. The IPEP data gave feedstock prices as the prices currently achieved for food use of OSR, SB and WW in Belarus. These were used in the base modelling cases, but we believed that lower prices might be acceptable for crops used as fuel. Lower prices for the feedstock were therefore also modelled, where these would still give the farmer a net margin of at least 100 EUR ha^{-1}.

Very few data were available for the by-product prices in Belarus. However, it was important to consider the by-product income, as they are an important contribution to the economics of liquid biofuel production. We assumed that they would be subject to international trade prices and therefore similar to those in W.Europe. Even so, the prices are subject to fluctuations, and so a sensitivity analysis was carried out on the effect of by-product prices. Moreover, for Belarus, there is the possibility that the by-products will be too contaminated for use, so this scenario was also modelled.

2.1.2 Information for Western Europe

Information was collected from both Belgium and the UK. By using a combination of these two data sources, we obtained sufficient information to model the production of RME from OSR and bioethanol from BS and WW.

2.1.2.1 Source of data for Belgium

UCL compiled some data on annual crop production for Belgium. The data covered Winter Wheat (WW), Sugar Beet (SB) and Oil Seed Rape (OSR).

- The data on the farm machinery for Belgium was similar to that for the UK which was already in CRISP. The CRISP machinery table was therefore retained.
- The data for WW and SB was fairly complete, and so the Western Europe run for these crops was based on the Belgian data. The data for OSR was missing some important information on the production operations. The data which was given was checked against the UK data, and the two were similar. Since the UK dataset was complete, and the two datasets were similar, the UK data was used for the W. European run for OSR for CRISP.
- The data provided from Belgium on conversion for annual crops was very limited. It comprised the name of the main product and by- products, and the price expected for these products. The yield of the main products was stated, but not the yield of the by-products. This was not enough information to model the conversion process in CRISP, which requires details about the costs of the conversion plant. Data from UK studies was therefore used to model the conversion processes. However, there was a substantial difference between estimates of the prices obtained for the main and by products of the conversion process. These differences existed between the Belgian and UK estimates, and within the different UK estimates considered. In the analysis the sensitivity of the system to price of all the products was therefore considered carefully.

2.1.2.2 Sources of data for the UK

Information on production of WW, SB, and OSR in the UK was obtained from Nix (1997). This is updated annually, and the data used are therefore considered to be the best available in the UK.

A review of the literature was undertaken to obtain information on the conversion processes. A range of material was considered, and that most relevant to the RECOVER project was incorporated into the CRISP model.

Our reservation about these data is that they are based on reports dating from 1994. We attempted to obtain more up to date information on conversion to liquid biofuels, but the information was commercially sensitive. We also contacted the author of the original reports to see if the data was still valid (Kerr Walker, personal communications). His view was that the costs of conversion would have remained constant or slightly increased, since the technology is mature. One development highlighted was the introduction in the USA of conversion plants at large starch processing works. In these cases the conversion plants fed with 'waste' starch which is unsuitable for food applications, so the feedstock is very low cost and the conversion plants are profitable. Unfortunately this scenario is not suitable for the Belarus situation, where the contamination levels will preclude food use, so this avenue was not pursue further.

2.2 Important system parameters for Western Europe/ Belarus comparison

2.2.1 Yield

The potential and actual yields for Belarus and the actual yields for W.Europe are shown in the table below.

Yield, t ha^{-1}	OSR	SB	WW
Belarus, potential	3.0	55	10.0
Belarus, actual	2.0	25	3.2
W.Europe, actual	3.2	66	7.5

These figures show that although Belarus has good potential for each crop, the actual yields achieved are much lower than this, and also much lower than those in W. Europe. Since for annual crops the production costs up to and including harvesting are on a per hectare basis, the low yields have a significant impact on the farmers net margin.

2.2.2 Labour

Labour costs in Belarus are at least a factor of 10 lower than in W.Europe. This leads to lower running costs of conversion equipment. On the production side, the low cost of labour means that more operations are carried out manually, or using less automated equipment. For this reason it is important to model the Belarussian equipment and techniques in the production phase. This has been achieved by using the information obtained by IPEP for Belarus.

2.2.3 Machinery

Machinery produced in Belarus is considerably cheaper than its counterpart in W. Europe. For example a tractor can be up to five times cheaper to produce in Belarus. For this reason, and because of simpler equipment design, the Belarus production machinery is much cheaper than that in W.Europe. For conversion equipment, again equipment which is already produced in Belarus could be cheaper than an equivalent in W. Europe. However, for specialised equipment not currently produced in Belarus, the cost of importing the equipment, or producing in Belarus, is likely to be similar and of the same order as the cost of the equipment in W.Europe. Since there is no large scale conversion to liquid biofuels in Belarus, the cost of such plant is therefore assumed to be the same as estimated for W.Europe.

2.2.4 Grants

No grants are presently available in Belarus. In contrast, energy crops in W.Europe may qualify for set aside grants or area payments. Tax relief is also available in some W.European countries to enable the liquid biofuel to be competitive as a transport fuel.

2.2.5 Sale of by-products

All the conversion processes considered produce valuable by-products which can contribute significantly to the viability of the conversion process. The prices obtained for these by-products may be subject to considerable fluctuation. This is due to the products having competition from alternative products on the world market, and the possibility that large scale production of some of these products may lead to a decrease in the market price. There is no information on the value of these products in Belarus, so we have assumed that they will fetch the international market price. In the case of Belarus, there is a real possibility that the by-products may be too contaminated for sale.

2.3 Sensitivity analysis for liquid biofuel production from annual crops

The factors considered for the sensitivity analysis are those which whose value may be subject to a large variation, and which we believe may have a large impact on the overall economics of the system considered. These are yield of crop, crop price, by-product income, conversion plant capital cost and transport cost. These are considered one by one below.

2.3.1 Yield

We assume that the yields for W.Europe are likely to remain at the levels quoted in the literature. For Belarus, SCK wanted to consider both the potential and actual yields for the crops. The table below summarises the effect on net margin of changes to yield in Belarus. We assume that the harvesting costs remain the same per hectare irrespective of the yield. For SB and OSR there is no change to the management regime between actual and higher yield. For WW we had the data to model low and high input scenarios. The results show that net margin increases with yield in all cases, but that the increased effort and cost required to boost yield must be considered carefully, as it does not necessarily lead to an equivalent increase in net margin. This is particularly a consideration in Belarus, where availability and cost of agrochemicals may be a problem for farmers.

Net margin as a function of yield for Belarus

	OSR@166EUR t^{-1}	SB@25EUR t^{-1}	WW@160EUR t$^{-1,*}$
Yield, t ha^{-1}	2.0	25	3.2
net margin, EUR ha^{-1}	128	137	321
Yield, t ha^{-1}	2.7	55	6.4
net margin, EUR ha^{-1}	188	744	600
Variation in yield,%	35	120	100
Variation in net margin, %	47	503	87

* WW high and low inputs modelled

2.3.2 Crop price

The price for the crops quoted for all three crops are the food prices achieved. For W.Europe, prices for OSR are available for industrial OSR, and for SB for non quota sugar . These lower prices have been considered for W.Europe, and also a general approach has been taken of reducing the price of the crop to that which would produce the minimum acceptable net margin for the farmer. This figure is of course subjective, and is estimated to by 225 EUR ha^{-1} for W.Europe and 100 EUR ha^{-1} for Belarus.

As well as impacting on the farmers income, the price of the crop is the single most important variable in determining the viability of the conversion process. In general we have found that if the crop is produced specifically as a feedstock for the conversion process, then it is too expensive for the conversion to be viable without price support. In the case where a feedstock is available at little cost, i.e. essentially a waste product, then the conversion process approaches viability.

The table below shows the cost in Belarus of biodiesel production estimated for the prices of crops :

- obtained when sold for food
- possible energy prices.

	OSR**	SB		WW	
	food use	food use	energy use	food use	energy use
Price, EUR t^{-1}	166	60	25	160	107
Farmers net margin, EUR ha^{-1}	120	1012	137	321	151
Cost of RME, EUR t^{-1}	390	>756*	430	>756*	575

* Maximum price achieved in W.Europe

** Net margin already low at quoted price.

2.3.3 By-product income

In all cases the by-product income is an important contribution to the economics of the conversion operation. For Belarus it is particularly uncertain, because the value of the by-products in Belarus is not known, and there is a real possibility that the by-products will be too contaminated for sale. The effect of by-product income has therefore been looked at in detail in the individual scenarios. Here we present a summary showing the effect on cost of biodiesel when the by-product income is at the assumed international market levels and when there is no by-product income.

	OSR		SB		WW	
Including by-product?	**Yes**	**No**	**Yes**	**No**	**Yes**	**No**
Meal @191EUR t^{-1} Glycerine @511EUR t^{-1}	390	745				
Pulp &vinasses @95 EUR t^{-1}			430	530		
DDG @135 EUR t^{-1}					585	730
% increase in cost for no by-products		91		24		25

The table shows that production of RME from OSR is the most sensitive conversion process to changes in by-product income. In fact, although the cheapest liquid biofuel to produce including by-products, it becomes the most expensive without them. It is therefore probably less well suited to the conditions in Belarus.

2.3.4 Conversion plant capital cost

For RME production, estimates of capital cost for Belarus were taken from the GOPA report. They gave a 'best' estimate which we used as our base case, but also said that Belarussian sources had estimated that plant could be built for 50% of this price. We therefore modelled both cases. The effect of reducing the capital cost by 50 % was to reduce the price of the RME by 22 %.

For bioethanol production from WW, we had no figures relating to the situation in Belarus. We therefore assumed that the cost of new capital equipment in Belarus was likely to be the same as in W.Europe. We modelled the cost of capital equipment on a greenfield site for the same price as W.Europe, and 80 % of this price, and also the cost of building a fermentation plant only, in case there are pre-existing starch processing facilities. The cost of bioethanol is reduced by 6 % if the starch processing plant already exists.

For bioethanol production from SB, again we had no figures from Belarus, but we did know that the amount of SB currently produced in Belarus is very small. We do not know if existing 'Beet end' processing equipment exists in Belarus, and is now disused, or if no equipment exists. We therefore modelled both cases. Assuming only the fermentation equipment is to be built, the cost of bioethanol is reduced by 12 % is the capital cost is halved. If the beet end equipment is also to be built, then the scheme will be prohibitively expensive.

2.3.5 Transport

The RME and bioethanol plant modelled are large scale, so that transport is potentially an important factor. Our standard assumption is that the average transport distance will be 40 km. However, for the low yields achieved in Belarus, it is possible that distances of up to 100 km will be required. For Belarus, the transporter detailed in the IPEP data is 5 t load, but this has been quoted for shorter journeys. A larger transporter is likely to reduce the transport costs, if available. The results show that the larger transport distances do not impact greatly on the costs of transport, partly because a higher average speed is assumed for the greater transport distance.

3 Individual cases modelled

The following section contains detailed descriptions of each of the cases modelled. These are

1. Western Europe large scale production of RME from OSR
2. Belarus small scale production of RME from OSR
3. Belarus large scale production of RME from OSR
4. Western Europe large scale production of bioethanol from SB
5. Belarus large scale production of bioethanol from SB
6. Western Europe large scale production of bioethanol from WW
7. Belarus large scale production of bioethanol from WW

3.1 Western Europe large scale production of RME from oil seed rape, 30000 t y^{-1} RME

3.1.1 Data sources

The data entered into CRISP was UK data. However, the UK data were checked against the available Belgian data, and the two were found to be comparable, so the CRISP run can be taken to be representative of the W. European case.

- Crop price in the base case is 165 EUR t^{-1} seed, from the UK study on biodiesel.
- We assume a set aside grant of 487 EUR ha^{-1} is payable
- The crop receives 3 lots of fertilisation and 2 sprays in the year.
- At harvesting, the crop is swathed and then combined.
- Storage is in an existing building, using portable grain walling. No drying is included.
- Transport is assuming a 40 km distance to the processing plant.

We have used data from earlier UK studies (Walker, 1994 a, b). These studies attempt to break down the production costs and to look at different scales of production and considered large-scale plants, 20,000 t y^{-1} seed to 90,000 t y^{-1} seed. For W.Europe we thus looked at large scale production.

3.1.2 Key Input Parameters

Variable	Base case	with grants
Yield, t ha^{-1}	3.2	
Area of OSR, ha^{-1}	27300	
Price for OSR seed, EUR t^{-1}	165	
Grants included	No	yes
Crop suppliers discount rate, %	8	
Conversion plant capacity, t h^{-1}	13	
Conversion discount rate, %	20	
Price of RME, EUR t^{-1} with price support	390 (1st year only)	390 (all years)
with no price support	187	
Price of meal, EUR t^{-1}	150	
price of glycerine, EUR t^{-1}	675	
Capital cost of conversion, MEUR	21	
Operating cost, MEUR y^{-1}	2.8	

3.1.3 Key Output Parameters

Variable	Base case	with grants
OSR producers net margin, EUR ha^{-1}	-208	280
OSR producers NPV, EUR ha^{-1}	-1507	3000
Conversion NPV, MEUR	$^{-1}$8	0.7
Conversion IRR, %		20

3.1.4 Sensitivity analysis

OSR is a well known crop in W. Europe, and the costs and likely yields are well known. On the production side, the crop is not profitable without the set aside payment of 488 EUR ha^{-1}. With the grant OSR becomes an attractive option. It has been suggested that OSR may be grown with lower input for fuel use. However, the impact on yield and seed quality of such a regime is not known. In any case, even if the yield and quality were maintained and the management cost reduced to zero, then the net margin for the crop without grants would only be about 60 EUR ha^{-1}.
It has been suggested that the OSR straw could be another income stream for the crop producer. The profit a producer is likely to make on straw is about 6 EUR t^{-1}, which could lead to an increase of about 5 % in the producers net margin.

The effect of price achieved for the grain is shown below

Variable	Base	Base	1	2
		with tax relief		with tax relief
grain price	165	165	195	195
Crop suppliers net margin, EUR ha^{-1}	-208	-208	$^{-1}$14	$^{-1}$14
Conversion NPV, MEUR	$^{-1}$8	0.7	-37	$^{-1}$3
Conversion IRR, %		20		

If the full food price were to be achieved for the seed, the production grant would still be required, and the conversion would now make a loss.

On the conversion side, things are less well known. The capital cost and running cost of the plant used are thought to be at the low end of the range, since the plant modelled is a large scale plant. Data presented in both UK and GOPA reports suggest that the cost of RME production will rise as the plant size decreases.

In addition to the main product of RME, there are by products with commercial value. These are meal for animal feed cake and glycerine. Estimates in the UK and Belgium for prices achieved for these products are

Product	UK , EUR t^{-1}	Belgium, EUR t^{-1}
Meal, 0.58 t t^{-1}	120^{-1}80	175
Glycerine, 0.04 t t^{-1}	675^{-1}050	279

This table shows that the market for animal feed is well defined, but that the glycerine price is subject to large fluctuations. In addition it has been suggested that if large quantities of glycerine are produced as a by product of RME production , then the price of glycerine will drop. The table below shows the sensitivity of the profitability of the conversion operation to the by product prices.

Meal	**120 EUR t^{-1}**	**150 EUR t^{-1}**	**180 EUR t^{-1}**
(glycerine at 675 EUR t^{-1})			
Conversion NPV, MEUR	-6.3	2.5	11.3
Glycerine	**279 EUR t^{-1}**	**675 EUR t^{-1}**	**1050 EUR t^{-1}**
(meal at 150 EUR t^{-1})			
Conversion NPV, MEUR	-5.6	2.5	10.1

The system is more sensitive to the changes in the meal price, due to the larger volumes of meal produced. However, both by products make a significant contribution to the profitability of the system.

3.1.5 Conclusion

RME production from OSR is only profitable in W. Europe with both production grants and price support for the RME(assuming the RME will be competing with mineral diesel for a market).
The by-products, meal for animal feed cake and glycerine, make an important contribution to the profitability of the conversion operation.

3.2 Belarus small scale production of RME from oil seed rape

3.2.1 Data sources

The data sources part of this scenario is relevant to both small and large scale production of OSR in Belarus. The production data is taken from the RISO/ IPEP data. The conversion data is taken from GOPA (1996)

3.2.2 Assumptions

The GOPA report reviews the technology used for RME production and the costs for Germany and Austria. The table below is derived from the report, and shows the way production costs vary with size of plant.

Type of plant	Scale, t y^{-1}	Cost, EUR l
Decentralised small scale	1500	0.96
Centralised small scale	10000	0.62
Centralised annex to oil mill	40000	0.48
Centralised large scale	100000	0.46

The difference in cost with scale is explained as a difference in process technology for the different scales. The small difference between 40000 t y^{-1} and 100000 t y^{-1} plant is explained because the technology has reached optimum size at 40000 t y^{-1} and because the 100000 t y^{-1} plant is not an annex to an oil mill.

The cost of RME in these estimates is higher than that from the UK case described, and at the top end of the costs quoted in the Belgian data. The table below shows the estimated costs for a 30000 t y^{-1} RME plant from the CRISP model. The first case is the UK best estimates for seed and by-product costs, and the second case the GOPA estimates for these parameters.

Case	Parameters	Cost, EUR l^{-1}
UK, 30000 t y^{-1} RME	UK estimates	0.30
UK, 30000 t y^{-1} RME	GOPA estimates	0.38

When the input seed cost and output costs for meal and glycerine used by GOPA were run in CRISP, an output value of 0.38 EUR l was obtained. Since the CRISP run is for a 30000 t y^{-1} RME plant, the comparator on the GOPA data would be about 0.48 EUR L^{-1}, which is 20 % higher. The capital and running cost assumptions for this size of plant made by GOPA are not known, so there is likely to be a difference there. Overall, the cost comparison is considered to be satisfactory.

We wanted to look at 2 sizes of RME plant in Belarus, small and large scale. The GOPA report gives data for a 1500 t y^{-1} and a 10000 t y^{-1} RME plant. Two estimates are given in the report for the costs of these plant. One is based on plant designed in W. Europe and tailored to Belorussian requirements and the other on data from Belarus. The authors comment that the cost structure for the W.European plant is based on proven data, and that the cost estimates based on these data are more comprehensive and reliable than the lump sum estimates from Belarus. They recommend use of these data for estimating costs of RME production in Belarus.

As a base case we have therefore used the W.European capital estimate for the plant, amended to allow for some components being manufactured in Belarus, and with Belarussian labour rates for running and maintenance.

There is considerable variation in the estimates of the cost of the OSR seed feedstock and the by products of processing. The table below shows the estimates form the various sources.

Commodity	UK estimate	Belgian estimate	GOPA estimate	IPEP estimate
OSR seed, EUR t^{-1}	165	not given	212	166
Meal, EUR t^{-1}	150	175	191	not given
Glycerine	675	279	511	not given

Where possible we have used the IPEP data, otherwise GOPA data was used.

- The cost of OSR seed used in the runs is 166 EUR t^{-1}, as given in the IPEP data.
- No values are given for the by products in the IPEP data, so the values from the GOPA report are used.

3.2.3 Key Input Variables

Variable	Base case	with RME price support
Area of OSR, ha^{-1}	2600	
Price for OSR seed, EUR t^{-1}	166	
Grants included	No	no
Crop suppliers discount rate, %	5	
Conversion plant capacity, t h^{-1}	0.8	
Availability, %	76	
Conversion discount rate, %	10	
Price of RME, EUR t^{-1} with price support	420 (1st year only)	420 (all years)
with no price support	187	
Price of meal, EUR t^{-1}	191	
price of glycerine, EUR t^{-1}	511	
Capital cost of conversion, MEUR	3	
Operational cost, MEUR y^{-1}	0.19	

3.2.4 Key Output Variables

Variable	Base case	with RME price support
OSR producers net margin, EUR ha^{-1}	128	128
OSR producers NPV, EUR ha^{-1}	1394	1394
Conversion NPV, MEUR	-2.5	0.06
Conversion IRR, %	not calculated	10.3%

The base case shows that RME production is not profitable in Belarus without price support for the RME. The second case shows that the minimum price for RME must be 420EUR t^{-1} if the conversion plant operator is to meet his target rate of return.

3.2.5 Sensitivity analysis

Three parameters have been considered: capital cost, by-product income and yield

3.2.5.1 Capital cost

The capital cost of the plant was estimated by GOPA based on W. European equipment tailored to Belarussian requirements, and assuming some of the equipment could be built in Belarus. This was thought to be the most reliable estimate and was used in the base case. However, GOPA also say that estimates from Belarus suggest that the capital cost could be less than half the Western estimate. We have therefore looked at the effect of reducing the capital cost by 20 % and 50 %.

Capital cost, MEUR	RME cost, EUR t^{-1}
3.0	420
2.4	360
1.5	290

3.2.5.2 By product income

The income from the by- products glycerine and meal makes a contribution to the profitability of the conversion operation. The prices quoted by GOPA are thought to be optimistic, especially for the meal. We have therefore looked at the effect of halving the income from these by- products. In addition it is possible that the by-products produced from OSR in Belarus will be too contaminated for sale, so we have also modelled the case of no income from the by- products.

In the following table the OSR seed cost is 166 EUR t^{-1}. The table shows that if the by-products cannot be sold the cost of the RME increase by a factor of 1.8. In fact the cost will be greater than this because the meal and glycerine will require disposal.

Price of glycerine	Price of meal	Cost of RME
511	191	420
250	100	590
0	191	475
511	0	720
0	0	770

3.2.5.3 Yield

The yield in Belarus is assumed to be 2 t ha^{-1}. This is the top end of the estimate of 1.5- 2 t ha^{-1} from Belarus, but is considerably lower than the 3.2t/ha achieved in the UK. The data from UCL suggest that 2.7 t ha^{-1} might be achieved under optimum conditions in Belarus. We have therefore looked at yields of 1.5t/ha and 2.7 t ha^{-1}. This will not effect the price of RME, but the profit to the producer.

Yield, t ha^{-1}	net margin, EUR ha^{-1}	NPV, EUR
2.0	128	1394
2.7	188	2047
1.5	49	530

3.2.5.4 Conclusions

- If the producer can achieve 2 or more t/ha OSR seed at the costs quoted for Belarus, then he can make a reasonable profit on the crop, provided he can sell at the market price of 166 EUR t^{-1}.
- Even at the lowest capital cost considered in the study, the conversion plant operator cannot make a profit unless the price of RME is subsidised.
- If the by products cannot be sold because of they are too contaminated, then the cost of the RME increases by a factor of about 1.8. In addition, the cost of disposal of the by- products must be considered.

3.3 Belarus large scale production of RME fromoil seed rape, 10000 t a^{-1} RME

3.3.1 Assumptions

- The conversion plant is centralised, and comprises facilities for crushing the seed as well as RME production.
- The production data is taken from the IPEP data.
- The transport distance is assumed to be 40 km, because the plant is now centralised
- The conversion data is taken from the GOPA report (1996). The values for the W. European estimate, adjusted for Belarussian requirements, are used, together with estimates of the cost of labour in Belarus.
- The cost of seed is from IPEP, 166 EUR t^{-1}
- The price for glycerine and meal are from GOPA (1996)
  - meal 191 EUR t^{-1}
  - glycerine 511 EUR t^{-1}

3.3.2 Key Input Variables

Variable	Base case	with RME price support
Area of OSR, ha^{-1}	14000	
Price for OSR seed, EUR t^{-1}	166	
Grants included	no	no
Crop suppliers discount rate, %	5	
Conversion plant capacity, t h^{-1}	4.3	
Availability, %	75	
Conversion discount rate, %	10	
Price of RME, EUR t^{-1} with price support	410 (1st year only)	390
With no price support	187	
Price of meal, EUR t^{-1}	191	
price of glycerine, EUR t^{-1}	511	
Capital cost of conversion, MEUR	12.4	
Operational cost, MEUR y^{-1}	1.29	

3.3.3 Key Output Parameters

Variable	Base case	with RME price support
OSR producers net margin, EUR ha^{-1}	120	120
OSR producers NPV, EUR ha^{-1}	1303	1303
Conversion NPV, MEUR	$^{-1}$1.5	0.08
Conversion IRR, %	not calculated	10.1

The results show that the OSR producers profits are slightly lower for the large scale than the small scale production. This is because all the farming costs are assumed to be independent of scale, but the transport costs are greater for the centralised plant.

With no RME price support, the conversion operation is unprofitable. The price achieved for RME must be at least 390 EUR t^{-1} for the conversion plant operator to meet his target return.

3.3.4 Sensitivity analysis

Four parameters were considered: yield, transport distance, by-product income and capital cost

3.3.4.1 Yield

The yield in Belarus is assumed to be 2 t ha^{-1}. This is the top end of the estimate of 1.5- 2 t ha^{1} from Belarus, but is considerably lower than the 3.2 t ha^{-1} achieved in the UK. The data from UCL suggest that 2.7 t ha^{-1} might be achieved under optimum conditions in Belarus. We have therefore looked at yields of 1.5 t $ha^{-1}$and 2.7 t ha^{-1}. This will not effect the price of RME, but the profit to the producer.

Yield, t ha^{-1}	Net margin, EUR ha^{-1}	NPV, EUR	Transport distance, km
2.0	120	1303	45
2.7	206	2246	38
1.5	58	634	50

- For the large scale production, we consider that the yield achieved is likely to be at the top of the range for Belarus, i.e. about 2 t/ha^{-1}.
- The range of yields is large, and the difference to the net margin is also large. This is because OSR is an annual crop, and a high proportion of the cost is in the establishment and management of the crop. These costs are proportional to the area cultivated not the yield. In addition, the transport costs are greater when the area producing the crop is greater.

3.3.4.2 Transport distance

In the table below, yield is 2 t ha^{-1}. The costs of transport in Belarus are low. Distance travelled does not have a large impact on producers net margin.

Transport distance, km	Net margin, EUR ha^{-1}
45	120
23	122
90	115

3.3.4.3 By-product income

The income from the by- products glycerine and meal makes a contribution to the profitability of the conversion operation. The prices quoted by GOPA are thought to be optimistic, especially for the meal. We have therefore looked at the effect of halving the income from these by- products. In addition it is possible that the by-products produced from OSR in Belarus will be too contaminated for sale, so we have also modelled the case of no income from the by- products.

In the following table the OSR seed cost is 166 EUR t^{-1}. If the by-products cannot be sold the cost of the RME increase by a factor of 1.9. In fact the cost will be greater than this because the meal and glycerine will require disposal.

Price of glycerine	Price of meal	Cost of RME
511	191	390
250	100	560
0	191	445
511	0	690
0	0	745

3.3.4.4 Capital cost

The capital cost of the plant was estimated by GOPA based on W. European equipment tailored to Belarussian requirements, and assuming some of the equipment could be built in Belarus. This was thought to be the most reliable estimate and was used in the base case. However, GOPA also say that estimates from Belarus suggest that the capital cost could be less than half the Western estimate. We have therefore looked at the effect of reducing the capital cost by 20 % and 50 %.

Capital cost, MEUR	RME cost, EUR t^{-1}
12.4	390
10.0	360
6.2	305

3.3.5 Conclusions

- Yield is the most important parameter for the OSR producer. In order to make a reasonable profit, he must achieve yields at the top end of those quoted for Belarus, i.e.. 2 t ha^{-1}.
- The production of RME will require subsidy under any of the scenarios considered.
- Sale of the by-products of conversion makes an important financial contribution to the scheme. If the by-products are too contaminated for sale, the cost of RME production almost doubles.
- On the most likely scenarios, the cost of RME production is lower on the larger scale plant than the small scale plant. However, these figure are very dependent on the estimate of the capital cost of the equipment and of the prices achieved for the by-products. Both these parameters are subject to considerable uncertainty in Belarus.

3.4 Western Europe large scale production of bioethanol from sugar beet

3.4.1 Data sources

Production data was provided by UCL. Some information on production costs and co-product prices was provided by UCL. Information on the production process, capital and operating costs and an analysis of co-products was obtained from unpublished UK reports.

3.4.2 Assumptions

- The sugar beet is produced in the normal way for W.Europe.
- There is no storage of the beet.
- The initial processing of the beet takes place at an existing beet processing unit. (Cost of a new 'beet end' processing facility is estimated to be in excess of 50 MEUR).
- Average transport distance to the processing plant is 40 km.
- The bioethanol facility is large scale, producing 100000 l d^{-1} bioethanol.
- The by-products pulp and vinasses are combined and sold as animal feed. (No molasses is produced in bioethanol production).
- The yield of beet, price of beet, price of by-products and price of bioethanol for the base case are all taken from the UCL data.

3.4.3 Key Input Parameters

Variable	Base case	with grants
Area of SB, ha^{-1}	4400	
Price for SB, EUR t^{-1}	38	
Production Grants included	no	no
Crop suppliers discount rate, %	8	
Conversion plant capacity, t/h	41	
Conversion discount rate, %	20	
Price of bioethanol, EUR t^{-1} with price support		756
with no price support	210	
Price of pulp, EUR t^{-1}	95	
price of vinasses, EUR t^{-1}	95	
Capital cost of conversion, MEUR	18	
Operating costs, MEUR y^{-1}	3.7	

3.4.4 Key output parameters

Variable	Base case	with grants
SB producers net margin, EUR ha^{-1}	1239	1239
SB producers NPV, EUR ha^{-1}	11456	11456
Conversion NPV, MEUR	-46	4.2
Conversion IRR, %		25

3.4.5 Sensitivity Analysis

The production of sugar beet in W.Europe is well known, and the establishment, management and harvesting costs are in close agreement for the UK and Belgian data. The main parameters which will are subject to uncertainty and may cause a large effect in the profitability are the yield and price achieved for the beet, which are considered below. The effect of transport distance is also considered, since it is likely that all the bioethanol will be produced at one plant, and it is therefore possible that the beet may need to be transported up to 100km to the plant.

Yield, t ha^{-1}	66	60	50
At 38^{EUR}/t beet.			
Crop suppliers net margin, EUR ha^{-1}	1239	1061	762
Crop suppliers NPV, EUR ha^{-1}	11456	9810	7042

Price of beet, EUR t^{-1}	15	20	23	25	38	50
At 66 t ha^{-1} yield of beet						
Crop suppliers net margin, EUR ha^{-1}	-287	51	249	381	1239	2031
Crop suppliers NPV,EUR/ha	-2576	474	2304	3525	11456	18778
Conversion plant NPV, MEUR At 756^{EUR}/t bioethanol	30.0	24.8	21.4	19.1	4.2	-9.6

Transport distance, km	40	80	100
Transport cost, EUR t^{-1}	4.6	6.3	7.8
Crop suppliers net margin, EUR ha^{-1}	1239	1127	1024
Crop suppliers NPV, EUR ha^{-1}	11456	10413	9474

The tables above show that the most important parameter for the profitability to the producer is the price achieved for the beet. The producer needs to achieve at least 23 EUR t^{-1} to make a reasonable profit, and the profit is very sensitive to changes in price around this value. The table also shows that even at the highly subsidised price of 756 EUR t^{-1} bioethanol, the conversion plant operator cannot pay the price achieved for beet going into sugar production.

For the conversion of sugar beet into bioethanol, the cost of bioethanol will vary with the price paid for the feedstock and the price achieved for the by-products. In all cases we have assumed that the pulp and vinasses will be combined to produce an animal feed.

Cost of feedstock, EUR t^{-1}	15	20	23	25	38
Cost of bioethanol, EUR t^{-1} Pulp and vinasses 95 EUR t^{-1}	430	490	530	550	715

At 38 EUR t^{-1} beet and 720 EUR t^{-1} bioethanol

Cost of animal feed, EUR t^{-1}	90	95	110	120
Cost of bioethanol, EUR t^{-1} Pulp and vinasses 95 EUR t^{-1}	720	715	695	685

The tables show that over the range of by-product prices the variation to the bioethanol price is about 5 %. The feedstock cost is of greater importance in determining the bioethanol cost.

3.4.6 Conclusions

- It would not be feasible to build a bioethanol plant for sugar beet on a green field site, because of the high capital cost of the beet end processing. The scenarios therefore consider building a bioethanol plant at an existing sugar beet processing plant.
- Even under these conditions, the conversion of sugar beet into bioethanol requires subsidy under W.European conditions.
- For producers, the system is most sensitive to the price of beet achieved. This must be at least 23 EUR t^{-1}, although beet grown in excess of quota for sugar may be available at alower price than this (say 15 EUR t^{-1}).
- For the conversion plant operator, the cost of the feedstock is an important consideration, but even the lowest priced feedstock does not allow bioethanol to be produced without subsidy.
- The by-product revenue is fairly stable, and offsets the cost of bioethanol production by about 20 %.
- With the assumptions made in the base scenario, the cost of producing bioethanol is estimated to be 715 EUR t^{-1}.

3.5 Belarus large scale production of bioethanol from sugar beet

3.5.1 Data sources

Data for production of sugar beet came from IPEP.
There was no conversion data from Belarus, so the conversion costs were estimated from the W.European costs.

3.5.2 Assumptions

For production
- The price achieved for the sugar beet is 60 EUR t^{-1}, from IPEP data.
- Planting is with ordinary seed drill, followed by thinning of plants.
- A small trailed harvester is used.
- There is no storage, with beets transported directly to the plant.
- The average transport distance is 40km, using a 5 t trailer.

For conversion
- The same costs are used as for W.Europe, except that Belarus labour rates are used.
- The fermentation plant is built onto an existing beet processing plant.
- The price achieved for the by-products is the same as for W. Europe
- There is no price support for the bioethanol

3.5.3 Key Input parameters

Variable	Base case	most realistic
Yield of SB, t ha^{-1}	25	
Area of SB, ha^{-1}	11500	
Price for SB, EUR t^{-1}	60	25
Production Grants included	no	no
Crop suppliers discount rate, %	5	
Conversion plant capacity, t h^{-1}	41	
Conversion discount rate, %	10	
Price of bioethanol, EUR t^{-1} with price support		430
with no price support	210	
Price of pulp, EUR t^{-1}	95	
price of vinasses, EUR t^{-1}	95	
Capital cost of conversion, MEUR	18	
Operating costs, MEUR Ny	3.7	

3.5.4 Key output parameters

Variable	Base case	with grants
SB producers net margin, EUR ha^{-1}	1012	137
SB producers NPV, EUR ha^{-1}	11038	1501
Conversion NPV, MEUR	$^{-1}$07	0.3
Conversion IRR, %		10

3.5.5 Sensitivity analysis

Unless otherwise stated, the price of sugar beet used is 25 EUR t^{-1}, the yield is 25 t ha^{-1}, the transport distance is 40km and the capital cost is 18 MEUR, for the fermentation plant only.

3.5.5.1 Production

The parameters considered for production were the price achieved for beet, the yield of beet and the transport distance. Please note that the machinery used for sugar beet production in Belarus, as advised by IPEP, relates to a small area of sugar beet grown, currently 378ha. For the large scale unit described here about 11500 ha are required. It is possible that planters, harvesters and transport more like that used in W.Europe would be used on this scale.

Yield, t ha^{-1}	**25**	**55**
At 25 EUR t^{-1} beet.		
Crop suppliers net margin, EUR ha^{-1}	137	744
Crop suppliers NPV, EUR ha^{-1}	1501	8112

The transport distance and the harvesting time/ha^{-1} are assumed to be the same for the different yields. The yield of 25 t/ha^{-1} from the data on actual yields sent by IPEP. 55 t/ha^{-1} is the potential yield estimated by UCL. This corresponds to a high but achievable yield in W.European terms.

Price of beet, EUR t^{-1}	**15**	**25**	**38**	**60**
At 25 t/ha^{-1} yield of beet				
Crop suppliers net margin, EUR ha^{-1}	-112	137	462	1012
Crop suppliers NPV, EUR ha^{-1}	-1223	1501	5044	11038
Conversion plant NPV, MEUR (at 756 EUR t^{-1} bioethanol)	74	54	27	-18
Conversion plant NPV, MEUR (at 210 EUR t^{-1} bioethanol)	-15	-36	-62	-107

The price of 60 EUR t^{-1} quoted by IPEP is the price for sugar beet destined for sugar production. This is unlikely ever to be achieved for bioethanol production, and leads to a large conversion plant loss even at the Belgian subsidised price for bioethanol.

At the W.European price of 38 EUR t^{-1} for beet, and 756 EUR t^{-1} bioethanol, both producer and conversion plant make a substantial profit in Belarus.

However, we feel that the crop producer would accept the profit margin associated with a beet price of 25 EUR t^{-1}, and this has been used in subsequent runs and in the most realistic scenario. At 25 EUR t^{-1}, the cost of conversion to meet the conversion target return of 10% is 430 EUR t^{-1}.

Transport distance, km	**40**	**80**	**100**
Transport cost, EUR t^{-1}	3.9	5.4	6.6
Crop suppliers net margin, EUR ha^{-1}	138	99	68
Crop suppliers NPV, EUR ha^{-1}	1501	1074	745

The transport distance should be kept below 80 km to maintain the producers profit margin. However, these figures are based on the use of a 5 tonne transporter. If larger vehicles are used the transport costs for larger distances will reduce. The average speed for the 80 and 100 km journeys is assumed to be 50kpm, whereas it is 30 km for the shorter journey.

3.5.5.2 Conversion

Capital cost	**18 MEUR** W.European cost	**14 MEUR** full cost*0.8	**0.9 MEUR** full cost*0.5	**35 MEUR** full cost of (fermentation+beet end)*0.5
Cost of bioethanol, EUR t^{-1}	430	410	380	535

Recent evidence is that the cost of building new plant in Belarus will be between 80 % and 100 % of the cost in W.Europe. These costs are therefore displayed in the table. If the fermentation plant could be built in Belarus for 50 % of the W.European price, then the bioethanol price would be reduced by about 12 %.

The current amount of sugar beet grown in Belarus is very small. If there are no existing under-utilised or redundant large scale beet end processing plant in Belarus, then we estimate that this will be an additional 52 MEUR capital investment at W.European prices. The effect on bioethanol price is shown in the table.

by-product price, EUR t^{-1}	95	40	0
cost of bioethanol, EUR t^{-1}	430	490	530

We have assumed that the maximum value of the by products pulp and vinasses is realised by combining the two into an animal feed, worth 95 EUR t^{-1}. This price is the Belgian price, since no estimate was received from Belarus. If the by-products price is lower in Belarus, say 40 EUR t^{-1} then the cost of bioethanol is increased by 14 %. If the by-products cannot be sold because the levels of contamination are too high, then the cost of producing bioethanol is increase by 23 %, plus the cost of disposing of the contaminated material.

3.5.6 Conclusions

- Bioethanol cannot be produced in Belarus from sugar beet without price support.
- Under typical Belarussian growing conditions, the producer can make an acceptable profit if sugar beet is sold at 25 EUR t^{-1}.
- At this sugar beet price, cost of bioethanol ranges from 430 EUR t^{-1} for an optimistic scenario, to over 530 EUR t^{-1} if no by-products can be sold.
- This equates to a price subsidy of 220 EUR t^{-1} to 320 EUR t^{-1}.

3.6 *Western Europe large scale production of bio-ethanol from winter wheat*

We have assumed that the wheat is grown in the standard high input way for Western Europe. Only large scale conversion is considered, since previous studies have shown that the process is most likely to be economic at this scale.

3.6.1 Data Sources

Production data

- The data was taken from the Belgian data provided by UCL.
- Where Belgian data was not available, UK data was used.

Conversion data

- Belgian data was not available in the detail required for CRISP.
- Data from UK studies was therefore used. These data were from 1994.

3.6.2 Assumptions

- The Belgian and UK data for wheat production were found similar. This run is therefore considered representative of the W.European case.
- The conversion plant was assumed to be on a greenfield site.
- The average transport distance was taken as 40km.
- No allowance has been made for drying.
- Storage is assumed to be in existing buildings, with grain walling.
- The by-product DDG is assumed to be sold as animal feed.

There is considerable variation in the literature between estimates of the productivity of bioethanol and its associated by-products from wheat.

For bioethanol, estimates for the amount of bioethanol produced from 1 tonne of wheat range from 212 kg (UCL data) to 305 kg (Warren, 1994). This may in part be due to the use of wheat at different moisture contents, but even allowing for this the UCL figure is pessimistic. In this study we have used the value given by Warren (1994), relating to odt wheat, and allowed for a 16 % moisture content at harvest. We have therefore assumed that 1 tonne wheat(at 16 %moisture) produces 256 kg bioethanol and 280 kg DDG. There is also a small amount of bran produced, which is a low value product and is not included in the analysis.

3.6.3 Key Input Parameters

Variable	Base case	with grants
Area of WW, ha^{-1}	1200	
Price for WW, EUR t^{-1}	110	
Production grant, EUR ha^{-1}	no	set aside, 487
Crop suppliers discount rate, %	8	
Conversion plant capacity, t h^{-1}	13	
Conversion discount rate, %	20	
Price of bioethanol, EUR t^{-1} with price support		756
With no price support	210	
Price of DDG, EUR t^{-1}	135	
Capital cost of conversion, MEUR	32	
Operating costs, MEUR y^{-1}	3.6	

Key output parameters

Variable	Base case	with grants
WW producers net margin, EUR ha^{-1}	209	696
WW producers NPV, EUR ha^{-1}	1933	6435
Conversion NPV, MEUR	-57	0.5
Conversion IRR, %		20.4

The producer can make a reasonable profit, even without production grants, provided that the market price can be achieved for wheat grown for ethanol.

For conversion, at this feedstock price, the plant operator is just meeting his target rate of return with a price of 756 EUR t^{-1} for the ethanol and a good price for the DDG by-product.

3.6.4 Sensitivity analysis

3.6.4.1 Production

Recently low input methods of growing wheat have been tried, incorporating a clover understorey, (ref 8). This method leads to a reduction in the inputs of agrochemicals required, but also a reduction in yield. The analysis below shows the effect on farmers net margin, assuming the harvesting costs are the same for the lower yielding crop.

	high input	low input
At 110 EUR per t seed.		
Yield, t ha^{-1} at 16 % moisture	7.5	4.0
Management cost, EUR ha^{-1}	255	30
Crop suppliers net margin, EUR ha^{-1}	209	87
Crop suppliers NPV, EUR ha^{-1}	1933	810

Price of wheat, EUR t^{-1} seed	10	80	102	110	140
At 7.5 t ha^{-1} wheat seed					
Crop suppliers net margin, EUR ha^{-1}	-540	-16	153	209	509
Crop suppliers NPV, EUR ha^{-1}	-5000	-146	1411	1933	4706
Cost of bioethanol, EUR t^{-1} At 135 EUR t^{-1} for DDG	360	640	720	756	910

Farmers are likely to require a net margin of at least 225 EUR ha^{-1} on the crop in W.Europe. This equates to a cost of 756 EUR t^{-1} of bioethanol.
In the USA bioethanol plant are being built next to starch processing plant, and using low value starch as feedstock. If the feedstock is essentially a 'waste' product available at a nominal charge of 10 EUR t^{-1}, then bioethanol can be produced for 360 EUR /t.

Transport distance, km	40	80	100
	40 kpm av	56 kpm av	56 kpm av
Transport cost, EUR t^{-1}	7.7	10.5	13.1
Crop suppliers net margin, EUR ha^{-1}	209	187	168
Crop suppliers NPV, EUR ha^{-1}	1933	1730	1561

For such a large scale plant, it is likely that the transport distance will be greater than 40 km, perhaps up to 100 km.

3.6.4.2 Conversion

For W. Europe, the cost of the feedstock and price achieved for the by-products are likely to be most uncertain and to have most effect on the cost of bioethanol. The effect of feedstock price is shown above, assuming the by-product is sold at 135 EUR t^{-1}.
The effect of the price of the by-product DDG is shown below. The value 135 EUR t^{-1} used in the base case is thought to be the maximum likely to be obtained.

Contribution of by-product at 7.5 t ha^{-1} wheat seed

Cost of DDG, EUR t^{-1}	60	90	120	135
Cost of bioethanol, EUR t^{-1}	840	800	770	756

The discount rate for the conversion plant operator is set at 20% for all these cases. This is a high value, which is thought to be reasonable in the light of the perceived risks of bioethanol production. The main risks being securing the supplies of wheat at the right price over the 15 year lifetime of the project, and the reliance on subsidy of the product (and possibly the feedstock). We believe it is likely that if the discount rate is reduced to about 10% then the project payback time will be reduced to 10 years. The table below shows the effect of reducing the discount rate, with a 15 and 10 year lifetime.

Discount rate, %	**20**	**10**	**10**
Lifetime of project	**15**	**15**	**10**
Cost of bioethanol	756	620	670

If the plant were sited at an existing starch processing facility, then the capital cost of the plant would be reduced to the cost of the fermentation equipment, say 18 MEUR. This, together with a low cost feedstock would give the lowest available cost for bioethanol.

Capital cost, MEUR	**32**	**18**	**18**
Feedstock price, EUR t^{-1}	**110**	**110**	**10**
Cost of bioethanol, EUR t^{-1}	756	620	230

3.6.5 Conclusions

- Under the conditions found in W.Europe today, the cost of producing bioethanol is estimated to be 756 EUR t^{-1}.
- Bioethanol as a transport fuel therefore requires a substantial subsidy to compete with fossil fuels.
- In order to make really significant reduction in the cost of bioethanol, by a factor of 2 say, the feedstock cost must be greatly reduced. This could be achieved by using low value starches produced from an existing operation. This option is also likely to reduce the capital cost, since all the processing plant except the fermenting equipment will already exist. With this option bioethanol comes close to competing with fossil fuels.

3.7 *Belarus large scale production of bioethanol from winter wheat*

3.7.1 Data sources

- Production data was taken from the Belarus data provided by IPEP.
- Conversion data was the W.European data, with the labour rates for Belarus inserted.

3.7.2 Assumptions

- The conversion plant is a large scale plant built on a greenfield site, at the same cost as for a W.European plant.
- The by product of ethanol production, DDG, is sold as animal feed at 135 EUR t^{-1}.
- The wheat is produced in the standard way for Belarus, using less inputs than in W.Europe and smaller and simpler harvesting machines.
- No allowance is made for drying.
- Transport is assumed to be 40 km on average to the conversion plant.
- The price of wheat grain is 160 EUR t^{-1}, as advised by IPEP.
- The discount rate for the producer is 5 %, and for the conversion operation 10 %. The lifetime of the plant is 15 years.
- The conversion efficiency to bioethanol and DDG is assumed to be the same as in W. Europe.

3.7.3 Key Input Parameters

Variable	Base case
Area of WW, ha^{-1}	28000
Yield , t ha^{-1} grain at 16 % moisture	3.2
Price for WW, EUR t^{-1}	160
Production grant, EUR ha^{-1}	No
Crop suppliers discount rate, %	5
Conversion plant capacity, t h^{-1}	13
Conversion discount rate, %	10
Price of bioethanol, EUR t^{-1} with price support	756
Price of DDG, EUR t^{-1}	135
Capital cost of conversion, MEUR	32
Operating costs, MEUR y^{-1}	2.7

3.7.4 Key output parameters

Variable	Base case
WW producers net margin, EUR ha^{-1}	321
WW producers NPV, EUR ha^{-1}	3497
Conversion NPV, MEUR	-3.6
Conversion IRR, %	8

3.7.5 Sensitivity analysis

3.7.5.1 Production

The yield quoted in the IPEP data is 0.32 t ha^{-1} y^{-1}, which we believe is an error. We have assumed the yield is in fact 3.2 t ha^{-1} y^{-1}. The production system in Belarus is lower input, and this value is consistent with the yields from other low input systems. If the yield could be increased by a factor of two without increasing the harvesting costs, then the farmers net margin would increase substantially. However, it is unlikely that the necessary inputs would be procured in Belarus.

	high input	low input
At 160 EUR t^{-1} seed.		
Yield, t/ha at 16% moisture	6.4	3.2
Management cost, EUR/ha	236	22
Crop suppliers net margin, EUR/ha	600	321
Crop suppliers NPV,EUR/ha	6540	3497

The price of grain quoted in Belarus is very high, and makes the cost of bioethanol higher in Belarus than in W.Europe. The model was therefore run using the W.European price for grain, the price which gives Belarussian farmers 150 EUR ha^{-1} margin and the marginal price for waste starch of 10 EUR ha^{-1}.

Price of wheat, EUR t^{-1} seed	10	107	110	160
At 3.2 t ha^{-1} wheat seed				
At 135 EUR t^{-1} DDG				
Crop suppliers net margin, EUR ha^{-1}	-159	151	161	321
Crop suppliers NPV, EUR ha^{-1}	-1734	1648	1754	3497
Cost of bioethanol, EUR t^{-1} At 135 EUR t^{-1} for DDG	200	575	585	780

To achieve a margin of 150 EUR ha^{-1}, the price of grain must be at least 107 EUR t^{-1}, leading to a bioethanol cost of 575 EUR t^{-1}, assuming by-product income is also obtained
In the USA bioethanol plant are being built next to starch processing plant, and using low value starch as feedstock. If the feedstock is essentially a 'waste' product available at a nominal charge of 10 EUR t^{-1}, then bioethanol can be produced for 200 EUR t^{-1} in Belarus.

3.7.5.2 By product income

Price for DDG, EUR t^{-1}	0	70	135
cost of bioethanol, EUR t^{-1}	730	655	585

No price for DDG was given for Belarus. In the base case we assume it is similar to the W.European value for animal feed of 135 EUR t^{-1}. If, however, the price is lower by a factor of two in Belarus, this leads to an increase in the cost of bioethanol of about 12 %. It is possible that the DDG may exceed the limits set for contamination of feedstuff, in which case it cannot be sold. In fact it will then lead to a further cost for disposal. In this case the cost of bioethanol will be at least 25 % higher than in the base case.

For the large scale plant, and particularly at the lower yields achieved in Belarus it is likely that the transport distances will be greater than 40 km. The table below shows the effect of the larger transport distances. The speed given for the Belarussian vehicles is 30 kpm average, for a 5 km journey. We assume this will be maintained for a 40 km journey, but will increase to 56 kpm for journeys of 80 km or more.

Transport distance, km	40	80	100
	30 kpm av	56 kpm av	56 kpm av
Transport cost, EUR t^{-1}	5.5	5.6	7.0
Crop suppliers net margin, EUR ha^{-1}	321	320	316
Crop suppliers NPV, EUR ha^{-1}	3497	3490	3442

The transport costs do not vary much for the distances considered, and all are lower than for transport in W.Europe. However, this assumes that there is a suitable network of roads for transport in the grain producing region.

3.7.5.3 Conversion

The effect on the cost of bioethanol of changes in the price of grain as feedstock and the price achieved for the by product DDG have been considered above.

Most recent advice is that if a plant were to be built at a greenfield site, then the capital cost of the plant would be close to that in W.Europe. We have therefore used the full W.European cost as the base case, and also looked at 80 % of that cost . We do not know the current grain processing set up in Belarus, but it is possible with the amount of grain currently produced in Belarus that large processing plant already exists. If the bioethanol plant were sited at an existing starch processing facility, then the capital cost of the plant would be reduced to the cost of the fermentation equipment, estimated to be 18 MEUR.

Capital cost, MEUR	**32**	**26**	**18**	**18**	**18**
Feedstock price, EUR t^{-1}	**110**	**110**	**110**	**160**	**10**
Cost of bioethanol, EUR t^{-1}	**585**	550	505	700	115

The table shows that the greatest effect on the cost of bioethanol is the price of the feedstock. Unless this is essentially a waste product produced on site and transferred at a nominal cost to the fermentation plant, the production of bioethanol requires a subsidy.

3.7.6 Conclusions

- The scale of plant considered requires 28000 ha^{-1} wheat production. This is more than half the current production in Belarus. We do not know if there is potential for further wheat production on this scale for bioethanol production.
- Assuming the potential for wheat production exists, then if the farmers are to make a reasonable return on their crop, the bioethanol produced must be subsidised.

4 References

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Annex 3

Economic modelling of small-scale decentralised electricity production in Belarus

Table of contents

1 The ECOP-model

A full description of the ECOP-model can be found in the deliverable *Main economic parameters for the growing and the conversion of willow SRC: overview and sensitivity analysis* (Goor, 1998). In this model, both production and conversion are run together, for example by one farmer, a farmers' co-operation, a community. The pilot gasification plant described in this deliverable has actually been set-up being considered for decentralised electricity production at peak electricity demand (high availability, low production, high revenue per kWhe)

2 Model hypotheses (reference case)

- The reference case assumes an interest rate of 10 %, a rotation length of 3 years during 8 rotations (no cut-back after 1 year), a density of 15 000 cuttings ha^{-1} (price of cuttings : 0.062 EUR), mechanical plantation with an adapted planter (initially built for harvest of vegetables) and harvest with an adapted local forage harvester (special head : circular saws).
- Machinery and workforce characteristics were chosen as close as possible to common values in Belarus; they were taken from economic models databases (RECAP, ECOP) and from the data provided by IPEP. Cost of local machinery was used if the related data were available. If not a price ratio West/Belarus of 5 was used. Specialised machinery was quoted at import price.
- The gasification system for electricity production was of 350 kW capacity. Its cost price was calculated from the ratio of the prospected cost of an 830 kW gasifier (data from IPEP: 16 500 EUR) and the cost of a gasifier of the same capacity in Belgium: 388 375 EUR). This ratio of 23.5 obtained was then used to calculate the cost of a 350 kW gasifier in Belarus (11 000 EUR). This factor 23.5 difference in costs was considered very high since some of the gasifier components may have to be imported. Therefore a safety factor of 3 was applied, finally giving a plant cost of 33 000 EUR.
- The chips are assumed to be stored in existing barns; no storage building costs are therefore considered.
- For each operation, the salaries are calculated considering one engineer (0.5 EUR h^{-1}) and as many workers (0.3 EUR h^{-1}) as necessary.
- Neither inflation nor land cost are taken into account. All the common agricultural tools (tractor, soil preparation tools, etc.) are supposed to be the farmer's own property (no renting costs).
- The SRC is grown on "suitable" land (e.g. peaty soils); the expected yield corresponds therefore to the common reference value (12 t h^{-1} y^{-1} for a well-established plot – i.e. from 3 years after plantation).
- The power plant capacity is 350 kW and electricity is produced all along the year at 75 % availability. Considering the global consumption per capita (total = 970 kWh per inhabitant y^{-1}), the kWh produced are suffient to supply electricity to a small village of more or less 2400 inhabitants (decentralised production). This production requires 230 hectares of SRC plantation (considering average annual yield of 12 t ha^{-1})
- The cost of electricity (required for SRC production) has been fixed at the domestic price (0.0032 EUR kWh^{-1}). The selling price of the electricity produced in the gasifier is difficult to determine a priori (decentralised production of electricity in small-scale gasifiers does not yet exist in Belarus). The model was run with the industrial price (0.034 EUR kWh^{-1}). None of the cases modelled was profitable at the domestic electricty price of 0.0032 EUR kWh^{-1}.
- No subsidies are considered to evaluate the production, storage, transport and crushing costs. The project profitability could also be evaluated considering a land subsidy of 100 EUR ha^{-1} y^{-1} all along the SRC plantation lifetime (in order to compensate the loss of profit due to soil contamination). This value of 100 EUR corresponds to the potential net revenue of a wheat grown on the same soil (yield: 2.8 tons ha^{-1} grain; selling price: 0.18 EUR kg^{-1} grain – IPEP data).
- Financing of the conversion plant (gasifier + engine) is considered over 24 years with an annual repayment at 0 % interest.
- Before plantation, chemical fertilisers and organic manure are applied (common agricultural practice in Belarus). The crop is also fertilised after each harvest to compensate for the exports with the stems harvested. Weed control and pesticides are applied according to Belgian practice.
- Net present value (NPV) and internal rate of return (IRR) were calculated. For information on terms see Annex 1.

3 System profitability and sensitivity analysis

The relevant parameter values are presented for the reference case described above. The influence of changing some parameters is then studied. Only the values that have been changed are presented.

3.1 Harvesting method

Variable	Harvest in chips (ref.)	Manual harvest	Harvest in sticks
SRC cultivation	22.35 EUR odt^{-1}	19.88 EUR odt^{-1}	24.35 EUR odt^{-1}
SRC transport	0.75 EUR odt^{-1}	0.58 EUR odt^{-1}	0.58 EUR odt^{-1}
SRC storage	0.08 EUR odt^{-1}	0.10 EUR odt^{-1}	0.10 EUR odt^{-1}
SRC crushing	0.00 EUR odt^{-1}	5.63 EUR odt^{-1}	5.63 EUR odt^{-1}
NPV (global)	-100 308 EUR	-141 881 EUR	-210 937 EUR
NPV (ha^{-1})	-431 EUR	-644 EUR	-957 EUR
IRR (global)	4.86 %	1.80 %	not calculated (<0)

From SRC production to SRC crushing, the option "harvest in chips" is globally cheaper than manual harvest or harvest in sticks. The production cost is, however, lower for "manual harvest". The first option (harvest in chips) is interesting for Belarus because it can be carried out with local machinery. A more detailed analysis comparing the impact of workforce and machinery cost (data not presented) sensitivity analysis revealed that the lower global production cost in case of manual harvest is not only due to the very low workforce cost, but rather to the important difference between costs of workforce and machinery. The values for the NPV and IRR show the project is not profitable for the conditions evaluated

3.2 Land subsidy

Variable	No subsidy (ref.)	Subsidy: 100 EUR ha^{-1} a^{-1}
SRC cultivation	22.35 EUR odt^{-1}	10.33 EUR odt^{-1}
SRC transport	0.75 EUR odt^{-1}	0.75 EUR odt^{-1}
SRC storage	0.08 EUR odt^{-1}	0.08 EUR odt^{-1}
SRC crushing	0.00 EUR odt^{-1}	0.00 EUR odt^{-1}
NPV (global)	-100 308 EUR	90 427 EUR
NPV (ha^{-1})	-431 EUR	388 EUR
IRR (global)	4.86 %	14.49 %

A land subsidy makes the project profitable. The total subsidy (all along the SRC plantation lifetime) is : 100 EUR ha^{-1} y^{-1} * 230 ha * 26 y = 598 000 EUR (which is hardly realistic since it corresponds to 18-fold the gasifier-building cost).

3.3 Gasifier building cost

Variable	**33 000 EUR (ref.)** IPEP estimate x 3	**11 000 EUR** IPEP estimate	**258 500 EUR** Belgian estimate
NPV (global)	-100 308 EUR	-42 167 EUR	-692 091 EUR
NPV (ha^{-1})	-431 EUR	-181 EUR	-2973 EUR
IRR (global)	4.86 %	7.95 %	not calculated (<0)

The project is not profitable, even with low local building costs for the gasifier if a global IRR of at least 10 % is required. The situation is obviously worse when the building cost of the SRC-Gazel pilot gasifier (Belgian reference) is considered .

3.4 Cutting price

Variable	0.062 EUR (ref.)	0.025 EUR	0.1 EUR	0.00035 EUR*
SRC cultivation	22.35 EUR odt^{-1}	15.50 EUR odt^{-1}	29.20 EUR odt^{-1}	25.55 EUR odt^{-1}
NPV (global)	-100 308 EUR	66 389 EUR	-150 723 EUR	79 606 EUR
NPV (ha^{-1})	-431 EUR	285 EUR	-647 EUR	342 EUR
IRR (global)	4.86 %	14.94 %	4.42 %	20.11 %

* Price of cuttings produced manually from one-year old SRC plantation in Belarus

The price of cuttings directly produced in Belarus has been calculated as follows :

- Workforce required for SRC manual harvest : 92 h ha^{-1}
- Preparation of cuttings: 83 h ha^{-1}
  - Ideally, cuttings should be made taken from 1-year old plantations. At this stage, plants have 2 stems (on average) and 5 cuttings of 20 cm can be obtained from each stem, which means 10 cuttings plant^{-1} or 150 000 cuttings ha^{-1} (initial planting density : 15 000 plants ha^{-1}).
  - Time to prepare and handle cutting: 2 seconds per cuttings or 83 h ha^{-1}.

The total time required to produce the 150 000 cuttings from 1 ha is 92 + 83 = 175 h ha^{-1} . Since for plantation 15 000 cuttings ha^{-1} are needed, it follows that preparation of own cuttings will require 17.5 h ha^{-1} . Since the salary of a worker in Belarus is 0.3 EUR h^{-1}, this comes down to cost of 5.25 EUR ha^{-1} or 0.00035 EUR cutting^{-1}. It should be noted that this cost does not include the cost of machinery (circular saw, ...) nor the transport cost. Further, if high-yielding varieties were imported from Europe, there are often breeders' rights on these varieties which implies that these willows can only be propagated if a certain amount (in Europe 0.01 EUR per cutting) is paid to the breeder.

The price of SRC production varies from 15.50 to 29.20 EUR odt^{-1} when the price of cuttings is multiplied by a factor 4 (from 0.025 to 0.1 EUR cutting^{-1}). NPV and IRR values show that the global project is profitable for low prices of cuttings, particularly when the cuttings are locally produced. The impact of the price of cuttings on the NPV is concentrated on the three first years (i.e., the crop establishment phase).
If the capital cost of the conversion unit would be the prospected Belgian capital cost, the system is not profitable, even not at the lowest cutting price (data not shown)

3.5 SRC yield

Variable Surface required	**12 t ha^{-1} (ref.)** 233 ha	**10.5 t ha^{-1}** 265 ha	**6 t ha^{-1}** 460 ha
SRC cultivation	22.35 EUR odt^{-1}	25.55 EUR odt^{-1}	44.70 EUR odt^{-1}
SRC transport	0.75 EUR odt^{-1}	0.75 EUR odt^{-1}	0.75 EUR odt^{-1}
SRC storage	0.08 EUR odt^{-1}	0.08 EUR odt^{-1}	0.10 EUR odt^{-1}
NPV (global)	-100 308 EUR	-151 027 EUR	-397 129 EUR
NPV (ha^{-1})	-431 EUR	-568 EUR	-853 EUR
IRR (global)	4.86 %	2.92 %	not calculated (<0)

The SRC yield has an important effect on the area required to supply the gasifier, which influences SRC production cost (more cuttings; more surface to prepare, plant, maintain and harvest) and SRC transport cost (longer travels).
Since project profitability was not acceptable under reference case conditions with the higher yield, it is clear that project profitability will worsen with even lower yields.