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Greenhouse gas emissions from willow-based electricity: a scenario analysis for Portugal and The Netherlands

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Abstract

This study focuses on greenhouse gas emissions from power plants using willow as fuel compared to those using fossil fuels. More specifically, we quantify emissions of nitrous oxide (N_2O) from soils on which willow is grown, and compare these to emissions of carbon dioxide (CO_2) from fossil fuel-based power plants. The results indicate that use of willow for producing electricity instead of fossil fuels is often, but not always more environmentally friendly. This is because the soil emissions of N_2O may be lower or higher than the avoided emissions of carbon dioxide (CO_2) from coal or natural gas-fired plants, depending on the way the willow is grown. Emissions may be higher in case willow is grown under specific field conditions reflecting high fertiliser use on organic soils, relatively long rotations and low yields. We performed a scenario analysis that compares soil emissions of N_2O to fossil fuel (combustion) related CO_2 emissions for power generation in Portugal and The Netherlands. Scenarios for the year 2010 indicate that greenhouse gas emissions from power plants may increase by up to 15–20% relative to baseline trends, in case willow use is increased to 20% of the total fuel use in power generation. In case willow is grown under relatively favourable conditions, these greenhouse gas emissions may be at least 20% lower than the baseline.

Keywords: Willow; Electricity; Greenhouse gases

1. Introduction

Global warming is considered a potentially serious environmental problem and the use of fossil fuels for electricity production is one of its main causes (IPCC, 2001). Renewable forms of energy, such as biomass, are considered promising and environmentally friendly alternatives to fossil fuels (e.g. Dincer, 1999; Gupta et al., 2002).

In this study we focus on willow (Salix spp.), a woody plant, which is considered a promising renewable fuel in electricity production (Londo, 2002). It is typically grown in short rotation coppice (SRC). This means that the plants are cut near the ground level and re-grown as multiple shoots rather than a single stem. Willow might be harvested up to six times, normally at intervals of 3–5 years. After this cycle, the stumps can be removed and agricultural crops or more coppices can be re-planted (Larsson, 2002). Willow grows better in cold and wet areas (mainly in the North Hemisphere) and only a few species are indigenous from the Southern Hemisphere. Willow trees produce biomass in a short period of time and are among the fastest growing woody species (Warburton et al., 1997). Willow can grow with relatively low inputs of fertilisers. However, in willow plantation usually considerable amounts of fertilisers are used. After the harvest, willow may robustly re-sprout and the energy obtained from its use can be 20 times higher than the energy utilised to grow the crop (Boyd et al., 2000).

Some studies, however, indicate that renewable fuels are not always beneficiary for the environment (Abbasi and Abbasi, 2000; Olesen, 2003; Streets and Waldhoff,

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1999). An important reason to switch from fossil fuels to biomass fuels is that the carbon dioxide (CO_2) released during the combustion of the biomass can, in the short term, be captured again in biomass, provided that the biomass is re-grown (Leemans et al., 1996). Biomass fuels may therefore have net zero emissions of CO_2. Still, this does not necessarily mean that biomass fuels have zero greenhouse gas emissions. For instance, during the combustion of any fuel, small amounts of other greenhouse gases such as nitrous oxide (N_2O) and methane (CH_4) may be released. Also the growth conditions of biomass are known to affect the energy efficiency of biomass fuels (Nonhebel, 2002). In addition, during the growth of energy crops often fertilisers are used and fertilised soils are considered the most important sources of emissions of N_2O (Kroeze et al., 1999; Kroeze and Mosier, 2000). How these biogenic emissions of non-CO_2 greenhouse gases compare to fossil-fuel related emissions is usually not included in studies comparing fuels. The studies that did include non-CO_2 greenhouse gas emissions during biomass growth in their analyses seem to indicate that these emissions are negligible compared to the emissions during combustion (IAEA, 1998). However, these analyses typically do not consider the wide range of cultivation practices that may influence the biogenic production of greenhouse gases during biomass growth. Therefore, the net effect of a switch from fossil fuels to biomass fuels on greenhouse gas emissions is not clear.

From the above may be clear, that the question to what extent renewable fuels like willow are a net benefit for the future environment is as yet unanswered. The purpose of this study is therefore to analyse the difference in greenhouse gas emissions from electricity production using willow as fuel, compared to using fossil fuels. To this end, we will first compare soil emissions of N_2O during growth of willow as a fuel, to CO_2 emissions from a fossil fuel-based power plant. Second, we will quantify these emissions for scenarios assuming that fossil fuels are replaced by SRC willow in electricity production in The Netherlands and Portugal in the coming decade. We take these two countries as arbitrary examples in our case study.

2. Methodology

In this study, greenhouse gas emissions from electricity production will be quantified. We do not aim to perform a full energy chain, or life cycle assessment. Rather, we are interested in how emissions during the growth of biomass compare to those during fuel combustion in power plants. This implies that other parts of the energy chain are not taken into account, which should be realised when interpreting the results. We did not include emissions during fossil fuel production, because these are typically small (Dones et al., 1998). We also did not include other greenhouse gas emissions to keep the comparison simple.

The emissions of CO_2 and N_2O will be quantified by using the IPCC Guidelines for National Greenhouse Gas Inventories (IPCC, 1997) and applying these to information available in the Regional Air Pollution Information and Simulation model—RAINS (Alcamo et al., 1990; IIASA, 2003).

Following the IPCC Guidelines, the emission of greenhouse gases from fuel combustion during electricity production are quantified as a function of fuel use and emission factors for power plants. In addition, emissions from fertilised soils are calculated as a function of fertiliser use and the emission factors for soils:

$$E_x = \mathrm{SUM}_i(\text{Fuel use}_i \times \text{EF power plants}_{x,i}) + \text{Emissions from soils}, \quad (1)$$

where E_x is the emissions of greenhouse gas x (CO_2) from electricity production (kg CO_2/year), EF power plants$_{x,i}$ the emission factor for greenhouse gas x (CO_2) during combustion of fuel type i in a power plant (kg CO_2/PJ/year), Fuel use$_i$ the amount of fuel i used in power plants (PJ/year), Emissions from soils the enhanced N_2O emission from soils during willow grown for fuelling power plants (kg CO_2-eq/year), calculated following Mosier et al. (1998), as described in detail below.

To convert N_2O emissions into CO_2-equivalents, a global warming potential (GWP) of 296 is used (IPCC, 2001). Moreover, kg CO_2-equivalents are converted to kg C-equivalents (1 kg CO_2 = 44/12 kg C).

The RAINS model (Alcamo et al., 1990; IIASA, 2003) is used as a basis for information on fuel use. Based on this information, a scenario analysis is performed for Portugal and The Netherlands for the period 1990–2010. For different scenarios the greenhouse gas emissions from power generation are analysed, assuming different amounts of willow used as a substitute for coal and natural gas in power plants. The emission scenarios take into account greenhouse gas emissions from fuel combustion in power plants, as well as N_2O emissions during the growth of willow. In the following, the methods used are discussed in more detail (2.1 and 2.2) and the scenarios are described (2.3).

2.1. IPCC Guidelines for National Greenhouse Gas Inventories applied to four cultivation types

The IPCC Guidelines for National Greenhouse Gas Inventories (IPCC, 1997) have been developed to assist countries in estimating their annual country level emissions of greenhouse gases (CO_2, N_2O, etcetera) from, for instance, fuel combustion in power plants and the nitrous oxide (N_2O) emissions from fertilised soils.

In this study, emissions factors for CO_2 for coal and natural gas combustion in power plants are taken from the IPCC Guidelines (IPCC, 1997). For combustion-related emissions from a willow-based power plant we assumed that CO_2 emissions are zero.

For soil emissions, two sources of N_2O are distinguished by IPCC: direct emissions from fertilised soils and N_2O emissions indirectly induced by fertilisation (Mosier et al., 1998). For the present research, only the relevant parts of the IPCC N_2O soil emissions calculations as described by Mosier et al. (1998) are used. The direct emissions refer to enhanced N_2O formation by bacterial processes (nitrification and denitrification) in fertilised and/or cultivated soils and may differ between mineral soils and organic soils. The indirect emissions of N_2O take place at remote sites and result from nitrification or denitrification of nitrogen that is lost from the agricultural system through leaching and runoff and through fertilised-induced atmospheric deposition of nitrogen compounds.

The emissions of N_2O in soils during willow growth, are affected by a number of variables, including the amount of fertiliser used, the number of years of willow growth before harvest, the type of soil and the willow yield. Based on these variables we developed four different cultivation cases (the no, low, average and high case) for two soil types (mineral and organic) (Table 1). These cultivation cases differ in terms of fertiliser input (0–120 kg N/ha/year), rotation time (2–5 years) and yield (0.15–0.4 TJ/ha).

- The *average case* is based on Londo (2002) and assumes that willow is grown in a 3-year rotation, during which the soil is fertilised with 100 kg N/year, resulting in a typical yield of 0.3 TJ/ha (per 3 years).

We want to analyse not only this average case, but also more extreme cases in terms of fertiliser input and yield. Therefore, we defined three alternative cultivation cases:

- *No fertiliser case*, assuming no fertiliser use, 2 years of rotation and a below-average yield (0.15 TJ/ha).

Table 1
Fertiliser input, years of rotation and assumed yield for the four cultivation cases used in the analysis to quantify the N_2O soil emissions during willow growth

Cultivation cases	Fertiliser input (kg N/ha/year)	Years of rotation (Year)	Yield[a] (TJ/ha)
No fertiliser	0	2	0.15
Low fertiliser	60	2	0.4
Average fertiliser	100	3	0.3
High fertiliser	120	5	0.2

[a]Assumed total yield after 2–5 years of rotation; assuming a primary energy input = 0.3 TJ/ha willow (Londo, 2002).

- *Low fertiliser case*, assuming moderate fertiliser inputs (60 kg N/ha/year), 2 years of rotation and an above average yield (0.4 TJ/ha).
- *High fertiliser case*, assuming high fertiliser inputs (120 kg N/ha/year), 5 years of rotation and a below average yield (0.2 TJ/ha).

The last case is chosen such that it favours high emissions. It resembles a situation where willow is growing slowly, despite relatively high fertiliser inputs. Even after 5 years of growing, the yield per hectare is still below average.

Different IPCC emission factors are used to quantify the direct and indirect emissions associated with willow growth (Table 2). *Direct* emissions refer to soil emissions of N_2O induced by nitrogen inputs (e.g. fertilisers) or cultivation. *Indirect* N_2O emissions take place at remote sites (terrestrial or aquatic), after transport of fertiliser N to these sites from the fertilised soil through leaching, runoff or volatilisation and consecutive deposition (Mosier et al., 1998). The IPCC Guidelines provide default emission factors for each of these N_2O sources, as well as uncertainty ranges for these emission factors. Table 2 summarises our choice of emission factors for the different cultivation cases. For the average cultivation case, we used the IPCC *default* emission factors for direct emissions, assuming that 1.25% of fertiliser N inputs is lost as N_2O; this is Emission Factor 1 (EF1) from Mosier et al. (1998). We also used the *default* emission factors for the indirect emissions caused by atmospheric deposition of N compounds originating from agriculture (EF4: 1% of N deposition is released as N_2O) and N inputs to aquatic systems ($EF5 = N_2O$ emissions amount to 2.5% of N inputs) from Mosier et al. (1998). For the low and high cultivation cases the lower and upper bound of the range in emission factors according to Mosier et al. (1998) are used (see Table 2). In addition to N_2O emissions associated with N inputs, cultivation of soils alone may cause extra N_2O formation. It is assumed here that the emission factor for soil cultivation (EF2) varies with the type of soil as recommended by IPCC ($EF2 = 5$ kg N/ha/year for organic soils (histosols) and 0 kg N/ha/year for mineral soils). For background information on these IPCC emission factors we refer to the overview by Mosier et al. (1998).

2.2. RAINS model

The information on fuel use in the power sector is taken from the Regional Air pollution Information System (RAINS) for Europe (version 7.2), developed at the International Institute for Applied Systems Analysis (Alcamo et al., 1990; IIASA, 2003). The RAINS model is a tool for integrated assessment of strategies to reduce transboundary air pollution problems in Europe.

Table 2
Values of the IPCC emission factors for quantifying N_2O emissions as used in this study (IPCC, 1997; Mosier et al., 1998)

	EF1 (kg N_2O–N/kg N input)	EF2 (kg N ha^{-1} year^{-1})	EF4 (kg N_2O–N/kg NH_3–N and NO_x–N emitted)	EF5 (kg N_2O–N/kg N leaching/runoff)
Mineral soils				
Cultivation case				
No fertilisation	NA	0	NA	NA
Low	0.0025	0	0.002	0.002
Average	0.0125	0	0.01	0.025
High	0.0225	0	0.02	0.12
Organic soils				
Cultivation case				
No fertilisation	NA	5	NA	NA
Low	0.0025	5	0.002	0.002
Average	0.0125	5	0.01	0.025
High	0.0225	5	0.02	0.12

NA—not applicable,
EF1 = emission factor for direct soil emissions.
EF2 = emission factor for organic mineralization due to cultivation.
EF4 = emission factor for indirect N_2O emissions induced by atmospheric nitrogen deposition.
EF5 = emission factor for indirect N_2O emissions induced by nitrogen leaching/runoff.
Organic soils are histosols or typical peat soils. Mineral soils are sandy soils.

RAINS Europe covers the European region, with a resolution of 150×150 km for atmospheric processes between the years 1990–2010. Here, we make use of national information from RAINS on fuel use within the power generation sector including fuel conversion in power plants.

2.3. Scenario description

2.3.1. Introduction

Scenario analysis is considered a powerful analytical tool to explore possible future developments (Alcamo, 2001; Nakicenovic et al., 2000). The purpose of the scenarios is to evaluate the impact different amounts of willow use for electricity on future greenhouse gas emissions in 2010 compared to 1990, for Portugal and The Netherlands. For the year 2010 three scenarios are analysed. These include a *baseline scenario*, and two alternative scenarios: the so-called *10% and 20% scenarios* (see below). These scenarios are to be considered hypothetical cases, meant to illustrate the potential impact of possible developments.

The scenarios differ with respect to assumptions about the type of fuel, the amount of fuel used and the percentage of replacement of fossil fuels by SRC willow for electricity production. For each scenario, the greenhouse gas emissions associated with electricity production (from combustion and during biomass growth) are analysed. Since we are interested in relatively high emission cases, our scenarios assume that willow is grown in organic soil.

The greenhouse gas (CO_2 and N_2O) emissions from electricity production are calculated for 1990, and for the three 2010 scenarios, including CO_2 emissions from combustion in power plants and the N_2O emissions from fertilised soils. For the 2010 scenarios, the emissions from willow-based electricity are quantified for four different cultivation cases (no fertiliser, low, average and high; Table 1). Moreover, for the 10% and 20% scenarios three fossil fuels substitution cases are analysed (assuming different fossil fuels to be replaced by willow; Table 3). This makes a total of 29 cases for organic soils (Table 3).

2.3.2. Reference year 1990

The greenhouse gas emissions from power generation in Portugal and The Netherlands are first quantified for the reference year 1990. This year is included in the analysis as a basis for comparison for the 2010 scenarios and because it is also the base year for the Kyoto Protocol, in which countries agreed to reduce their greenhouse gas emissions.

The emission estimates reflect total emissions from electricity generation, including emissions from fuel combustion in power plants and the soil emissions during biomass growth. It is assumed that in 1990 the biomass used in power plants is grown according the no fertiliser cultivation case.

2.3.3. Baseline scenario for 2010

The baseline scenario is based on the projections for future fuel use in the power sector in The Netherlands and Portugal from the RAINS 7.2 model under the default scenario. The RAINS default scenario includes information on fuel use by different economic sectors in the different European countries, as envisaged by these

Table 3
Description of the 29 cases distinguished in the scenario analysis for the year 2010 and the underlying assumptions

Scenarios	Cultivation cases				Fossil fuel substitution cases
	Soil type[a]	Amount of fertiliser[b]	Rotation years	Yield	
Baseline scenario[c]	Organic soils	No	2	Low	No substitution of fossil fuels by willow
	Organic soils	Low	2	High	No substitution of fossil fuels by willow
	Organic soils	Average	3	Average	No substitution of fossil fuels by willow
	Organic soils	High	5	Low	No substitution of fossil fuels by willow
10% scenario and 20% scenario[d]	Organic soils	No	2	Low	Mixed case—willow replaces coal and natural gas (ratio 60:40)
					Coal case—willow only replaces coal
					Gas case—willow only replaces natural gas
	Organic soils	Low	2	High	Mixed case—willow replaces coal and natural gas (ratio 60:40)
					Coal case—willow only replaces coal
					Gas case—willow only replaces natural gas
	Organic soils	Average	3	Average	Mixed case—willow replaces coal and natural gas (ratio 60:40)
					Coal case—willow only replaces coal
					Gas—willow only replaces natural gas
	Organic soils	High	5	Low	Mixed case—willow replaces coal and natural gas (ratio 60:40)
					Coal case—willow only replaces coal
					Gas case—willow only replaces natural gas
					Mixed case—willow replaces coal and natural gas (ratio 60:40)
					Coal case—willow only replaces coal
					Gas case—willow only replaces natural gas

[a]Organic soil: calculations as for histosols in IPCC (1997).
[b]No = 0 kg N/ha/year; low = 60 kg N/ha/year; average = 100 kg N/ha/year; high = 120 kg N/ha/year.
[c]No substitution of fossil fuels by willow.
[d]In the 10% and 20% scenarios it is assumed that willow replace 10% and 20% of fossil fuels in electricity production in 2010, respectively.

countries at the time version 7.2 of the RAINS model was developed. Based on this information, the total greenhouse gas emissions from power plants are calculated for coal and natural gas fired power plants. For power plants fuelled with biomass wood, greenhouse gas emissions are also calculated, including emissions from soils, during willow cultivation. The greenhouse gas emissions are estimated for the year 2010, for four different cultivation cases (Tables 1 and 3).

2.3.4. *Alternative scenarios for 2010*

Two alternative scenarios are formulated assuming different amounts of willow used in electricity generation. This extra willow is assumed to replace coal and natural gas use in power plants:

- *The 10% scenario*—assuming an increase in the use of willow as a fuel to 10% of total fuel use in power plants.
- *The 20% scenario*—assuming an increase in the use of willow as a fuel to 20% of total fuel use in power plants.

We realise that these scenarios do not follow current trends. Rather, they are reflecting *possible* futures, which may become realistic if renewable forms were to be promoted effectively.

These scenarios are analysed for four different cultivation cases (Tables 1 and 3). In addition, we distinguish between three different fossil fuels substitution cases (Table 3):

- *Mixed case*, in which willow replaces fossil fuels at an arbitrary ratio of 60:40 for coal and natural gas.
- *Coal case*, in which willow replaces only coal.
- *Natural gas case*, in which willow replaces only natural gas.

The 10% scenario is comparable to the European Union targets for the use of renewable energies in the short-term future, with a target year in 2010. This scenario shows the potential impact on the environment if the EU target would be met by an energy crop such as willow. The 20% scenario is meant to analyse the impact on the environment of more ambitious targets.

3. Emissions of greenhouse gases from willow versus fossil fuels-based power plants

Carbon dioxide emissions from power plants fuelled with coal and natural gas amount to 23.5 and 15.2 t C/TJ on average (IPCC, 1997). We first focus on the question to what extent replacement of fossil fuels by willow may reduce these emissions. To this end, emissions of greenhouse gases from a willow-based power plant, including emissions during willow growth are quantified in tons of carbon per TJ of electricity produced (Table 4). We included the total CO_2 greenhouse gas emissions released during the combustion of 1 TJ of willow in a power plant, compared to the enhanced N_2O emissions from soils during willow cultivation (in line with assumptions underlying Eq. (1)). The emission factors are calculated for a number of cultivation cases (see Table 1). Thus we compare the N_2O emissions from willow-based power, to CO_2 emissions from fossil-fuel based power plants (Table 4).

The results indicate that N_2O emissions from soils are relatively high for high fertiliser inputs (120 kg N/ha/year) in 5 years willow rotation with relatively low yield (the high fertilisation cultivation case) (Table 4). The N_2O emissions from power generation based on willow grown according to the high fertilisation cultivation case in organic soils amount to 38 t C/TJ, exceeding the emission factors for a coal-fired power plant (23.5 t C/TJ) and a natural gas fired power plant (15.2 t C/TJ) (Table 4). If willow is grown in mineral soils, 22 t C/TJ is emitted, which means that willow may be a good replacement for coal (23.5 t C/TJ) but not for natural gas (15.2 t C/TJ) in electricity production. For other cultivation cases with lower fertiliser inputs, shorter rotation and high yields, emissions are in general lower than from fossil fuel-based power plants.

From the above may be clear that when evaluating willow as a fuel, attention should be paid to the soil N_2O emissions during willow cultivation, since these can outweigh the avoided greenhouse gas emissions from fossil fuels. The fertilisation of the soil where the willow is cultivated, the rotation years and the yield are important variables, determining whether or not willow-based power plants emit more or less greenhouse gas emissions than fossil fuel-based power plants.

The difference in soil emissions of N_2O between the cultivation cases is calculated to be larger for organic soils than for mineral soils (Table 4). For instance, the difference in N_2O soil emissions between the average cultivation case (100 kg N/ha/year, 3 years rotation and average yield) and the high fertilisation cultivation case (120 kg N/ha/year, 5 years rotation and low yield) is about 19 t C/TJ for mineral soils and 29 t C/TJ for organic soils. In line with Mosier et al. (1998), the calculated direct N_2O soil emissions resulting from the input of fertiliser and soil cultivation are higher than the indirect soil emissions associated with nitrogen leaching and runoff and atmospheric deposition. For organic soils, the N_2O direct soil emissions from SRC willow grown with no fertiliser cultivation case (0 kg N/ha/year, 2 years rotation, and low yield) are higher than the emissions from low fertiliser cultivation case (60 kg N/ha/year, 2 years rotation, and high yield). This may be explained by the assumption that during willow growth

Table 4
Greenhouse gas emission factors for fuel combustion in power plants (CO_2) and soil emissions during the growth of willow in mineral and organic soils (N_2O). Units: t C/TJ

Types of power plants	GHG emissions during combustion in power plants[a]	Emissions from mineral soils[b]				Emissions from organic soils[c]			
		No fertilization case	Low fertilization case	Average fertilization case	High fertilization case	No fertilization case	Low fertilization case	Average fertilization case	High fertilization case
Coal	25.3	0	0	0	0	0	0	0	0
Natural gas	15.2	0	0	0	0	0	0	0	0
Willow	0	0	0	3	22	8	3	9	38

[a] *Source*: IPCC (1997).
[b] Assuming that willow is grown in mineral soils (see text).
[c] Assuming that willow is grown in organic soils (see text).

with no fertiliser cultivation case, the yield is low and more dry matter is necessary for production of one unit of electricity.

4. Emissions scenarios for The Netherlands and Portugal for 2010

Future trends in greenhouse gas emissions resulting from the use of willow in power plants in The Netherlands and Portugal are analysed for different scenarios: three scenarios for 2010 and a reference case for the year 1990 (reference year for the Kyoto Protocol). The greenhouse gases included in the analysis are CO_2 from power plants and N_2O during growth of biomass. We focus in particular on cases assuming that willow is grown in organic soils.

The first scenario for 2010 is a baseline, assuming no policies to increase the use of renewable energy. In this scenario, there is a substantial increase in calculated greenhouse gas emissions. The calculated 2010 emissions are about 2.5 times the 1990 emissions for Portugal, increasing from 2.1 to 5.2 Mt C/year (Fig. 1; no fertilisation case). For The Netherlands, the increase is more moderate (20%) from 11.6 Mt C/year in 1990 to 14 Mt C/year in 2010 (Fig. 2; no fertilisation case). For both countries the baseline emissions increase with increasing fertiliser use and years of rotation.

Two alternative scenarios assume an increase in willow used as fuel in power plants to 10% or 20% of total fuel use in the power sector (Figs. 1 and 2). The 10% scenarios show a reduction (2–6% for Portugal and The Netherlands) in emissions relative to the baseline, in case willow is grown with average or below average fertilisation rates (0 to 100 kg N ha^{-1} $year^{-1}$), in relatively short rotation ($\leqslant$3 years) and with relatively high yields. The 20% scenarios result in a larger reductions (5–17% for Portugal and 6–21% for The Netherlands) (Figs. 1 and 2) in the calculated greenhouse gas emissions relative to the baseline for all cultivation cases, except for the high fertilisation case.

The 10% and 20% scenarios show that the use of willow for producing electricity can be more environmentally friendly than using fossil fuels, even if willow is grown in organic soils. However, they also show that this is not always the case. Replacement of fossil fuels by willow may cause a significant increase in greenhouse gas emissions if willow is grown with high fertilisation inputs, in relatively long rotations (5 years or more) and with relatively low yields (the high fertilisation cultivation case). Thus, the environmental benefit of using willow for electricity production depends on soil type on which willow is grown, fertiliser input, years of rotation and yield.

For Portugal, lowest emissions are calculated for the 20% scenario, in which willow is grown with no or low

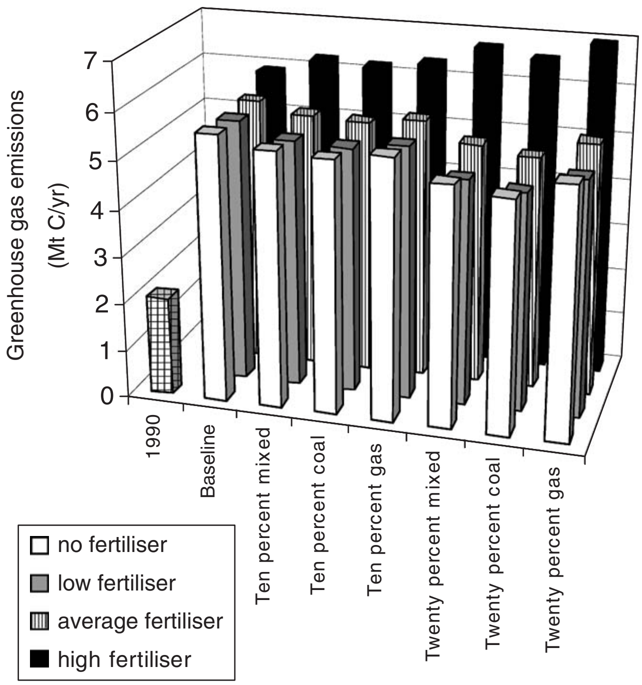

Fig. 1. Greenhouse gas emissions (CO_2 emissions during combustion and N_2O emissions from soils) for electricity production in Portugal for 1990 and the 2010 scenarios for the organic soil cases. The scenarios (baseline, 10% and 20%) are shown for different fuel cases (mixed, coal, gas) and for the different cultivation cases: no fertiliser cultivation case (organic soils, 2 years rotation, low yield), a low cultivation case (60 kg N/ha/year, organic soils, 2 years rotation, high yield), average cultivation case (100 kg N/ha/year, organic soils, 3 years rotation, average yield) and high cultivation case (120 kg N/ha/year, organic soils, 5 years rotation, low yield).

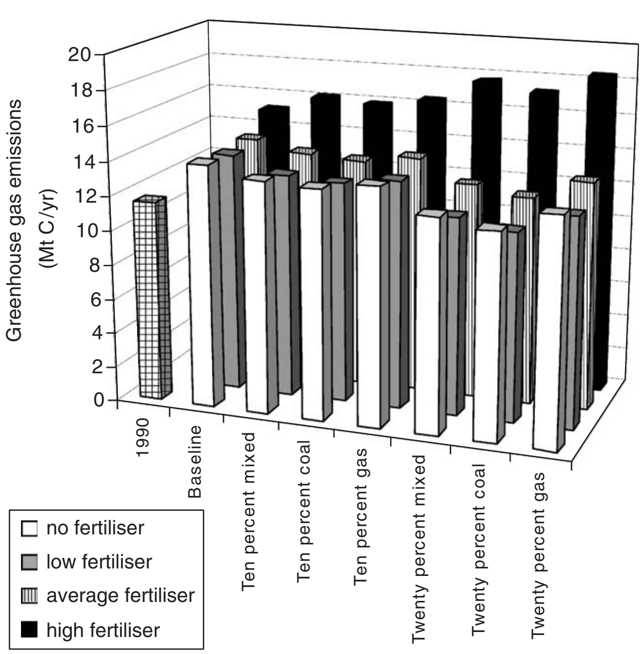

Fig. 2. As Fig. 1, but for The Netherlands.

N inputs (100 kg N/ha/year or less), and where willow is yielded after 2 or 3 years rotation. When willow is replacing coal, emissions may be 0.7–1 Mt C/year lower than in the baseline scenario (Fig. 1). However, when willow is grown in a 5 years rotation, with low yield and with high fertiliser N inputs (120 kg N/ha/year); emissions are calculated to amount to 7 Mt C/year, which is higher than the emissions from the baseline scenario (Fig. 1).

Likewise, for The Netherlands, emissions are lowest when willow is grown with no or low N inputs (100 kg N ha/year or less), and when willow is yielded after 2–3 years rotation. For instance, in the 20% scenario assuming this cultivation type, and when assuming that willow is replacing coal, emissions may be 2–3 Mt C/year lower than in the baseline scenario (Fig. 2). Emissions in the 20% scenario for low N inputs of fertiliser (100 kg N ha/year or less) are even lower than the 1990 level. However, when willow is grown in a 5 years rotation with low yield and with high fertiliser N inputs (120 kg N/ha/year); emissions are calculated to amount to 18.4 Mt C/year, which are higher than the emissions in the baseline scenario.

It is interesting to compare the 2010 scenarios to the 1990 situation. For Portugal, all 2010 scenarios have emissions exceeding the 1990 level. In other words, the assumed increase in willow use in electricity production alone may not be sufficient to reduce emissions to their 1990 levels. In The Netherlands, an increase in total greenhouse gas emissions from the power sector may be avoided in the 20% scenario, in which the emissions are calculated to be lower than their 1990 levels. It should be noted that our scenarios are worst cases, assuming that willow is grown in organic soils and ignoring non-CO_2 greenhouse gas emissions from power plants. It is also interesting to compare the two countries. The relatively large difference between Portugal and The Netherlands may be explained by the fact that the 1990 emissions in Portugal were relatively low, even compared to the 2010 baseline. The results indicate that a reduction in greenhouse gas emissions relative to the 1990 level may not be easily achieved in the scenarios for Portugal. Realising that these scenarios are quite ambitious in terms of use of renewable fuels, it may therefore be questioned whether increased use of biomass alone will be sufficient to meet the targets of the Kyoto Protocol. Note that all calculations for 2010 assume willow growth on organic soils, except for the no fertiliser-input case that considers as well the emissions from mineral soil.

The area of land needed for willow cultivation in the different scenarios for the year 2010, can be calculated by dividing the willow use (biomass wood in TJ) by the primary energy production per hectare (TJ/ha willow). Following Londo (2002), we assume that the primary energy production equals 0.32 TJ/ha willow.

For Portugal, we calculate that the land required for willow cultivation in the different scenarios (baseline, 10% and 20%) is relatively small. In the baseline scenario an area as large as 1% of the agricultural and non-arable land in Portugal would be sufficient. For the 10% and 20% scenarios, the required area for willow cultivation would be about 2% and 4%, respectively. If willow would be cultivated in non-arable land then it would cover only about 1% and 3% of that area in the 10% and 20% scenarios, respectively.

For The Netherlands, the land requirements for willow cultivation in the baseline scenario are higher than in those calculated for Portugal. For the 10% scenario an area for willow cultivation would be required equalling 14% of the agricultural land or 12% of non-arable land. In the 20% scenario the area needed may be 29% of the currently available agricultural land.

5. Conclusions

5.1. Greenhouse gas emissions from power plants

In this study, we first quantified the greenhouse gas emissions from fuel combustion per unit of electricity produced, using either fossil fuels, or willow as a fuel. The emission estimates include CO_2 formation during combustion of fuels, and N_2O emissions from soils associated with the cultivation of willow. We based our analysis on the IPCC Guidelines for National Greenhouse Gas Inventories (IPCC, 1997; Mosier et al., 1998) and information on willow cultivation (e.g. Londo, 2002). Although our analysis focuses on Portugal and The Netherlands in particular, the calculated emissions per unit of electricity produced may also be representative for other countries in temperate world regions.

The results indicate that the use of willow for producing electricity is not always more environmentally friendly than use of fossil fuels. Replacement of fossil fuels by willow may in fact result in a significant increase in greenhouse gas emissions in case willow is grown with high fertiliser inputs (120 kg N/ha/year) for relatively long rotations (e.g. 5 years) with relatively low yields on organic soils.

On the other hand, the greenhouse gas emissions from a SCR willow-based power plant (including emissions during willow growth and fuel combustion) can be also lower than the emissions from a coal or natural gas fired power plant, depending on the field conditions. These conditions are related to the type of soil (organic soils have higher N_2O emissions than mineral soils), amount fertiliser used (lower fertiliser rates result in lower emissions), years of rotation and willow yield.

The CO_2 emissions from an average power plant using natural gas are 15.2 t C/TJ and for a coal fired power plant are 25.3 t C/TJ (based on IPCC, 1997). The emissions from a willow-based power plant (from combustion and soil emissions), using willow grown in organic soil and high fertilisation cultivation case (38 t C/TJ) exceed these emissions (Table 5). For average fertiliser inputs (100 kg N ha^{-1} $year^{-1}$) to organic soils as assumed in the average cultivation case, however, this emission factor is calculated to be 9 t C/TJ (Table 5), which is below that of both coal and natural gas-based power plants. The same holds for willow grown following the below-average cultivation cases.

Following Mosier et al. (1998), we distinguish between *direct* soil emissions of N_2O (associated with fertiliser use and cultivation of the land) and *indirect* emissions, associated with nitrogen losses from the soil (through leaching and runoff, and through emissions to the atmosphere and consecutive deposition), giving rise to N_2O formation at remote sites. For willow cultivation we calculated that the direct N_2O emissions resulting from the input of fertiliser for willow growth and cultivation of the soil exceed the indirect emissions. For high fertiliser inputs (120 kg N/ha/year) on organic soils, 5 years rotation and low yield, direct N_2O emissions are calculated to amount to 17.2 kg N/ha/year. The total N_2O emissions (direct plus indirect) from willow cultivation on organic soils are always higher than for mineral soils. The indirect N_2O soil emissions associated with nitrogen leaching and runoff for the high fertilisation cultivation case can reach a value of 14.4 kg N/ha/year. The indirect emissions induced by atmospheric deposition are negligible: 0.2 kg N/ha/year.

5.2. Future emissions from Portugal and The Netherlands

Next, we addressed the issue of future trends in emissions from the power sector, under different assumptions on willow use as a fuel in the power sector for two illustrative countries: Portugal and The Netherlands. To analyse this, we used information on fuel use available in the RAINS model (Alcamo et al., 1990; IIASA, 2003) and the IPCC Guidelines for National Greenhouse Gas Inventories (IPCC, 1997; Mosier et al., 1998) to estimate greenhouse gas emissions (CO_2 emissions from power plants and soil emissions of N_2O during willow growth). A scenario analysis for Portugal and Netherlands was performed for the period 1990–2010. In all scenarios willow is assumed to be from organic soils. It should be noted that non-CO_2 greenhouse gases from power plants are ignored in this analysis. Since these are relatively small compared to CO_2 emissions, including them would probably not affect our conclusions.

5.2.1. Portugal

In 1990, the CO_2 emissions from power plants were 2.1 Mt C/year, of which most from fossil fuels-based power plants. In the baseline scenario, reflecting changes in fuel use as envisaged by countries in the late 1990's emissions increase between 1990 and 2010 (Fig. 1). In the baseline scenario, use of biomass fuels like willow is relatively low. The rate of increase in emissions depends on the level of assumed fertiliser use for willow production as well as on the years of rotation, the soil type and the yield. The 2010 emissions are a factor of 2.5 (no fertiliser use case) to 2.8 (high fertiliser use case) higher than the 1990 emissions.

In the 10% and 20% scenarios the effect of increased use of willow in electricity production was analysed assuming different conditions for willow growth (fertiliser input, years of rotation, yield) as well as different cases for fossil fuel replacement by willow (gas, coal or both). The results show a decrease or an increase in greenhouse gas emissions (CO_2 plus N_2O) depending on growth conditions for willow and type of fossil fuel replaced. In the 10% scenario, greenhouse gas emissions from electricity production are calculated to lower than in the baseline scenario (2–7% in the different cases), except when willow has low yield and is grown on organic soils that receive high fertiliser inputs for 5 years. In the latter case, the greenhouse gas emissions are 4–7% higher, depending on the type of fossil fuel replaced. In the 20% scenario for Portugal, the greenhouse gas emissions are 6–17% lower than in the baseline scenario, in the no, low and average fertiliser cultivation cases, and up to 18% higher in the high fertiliser cultivation case.

The largest emission reductions are calculated for the 10% and 20% scenarios, assuming replacement of coal by willow, grown according to the average or below average cultivation case. The implementation of the 10% and 20% scenarios by 2010 would, however, not avoid an increase in greenhouse gas emissions from power plants relative to the year 1990. This may indicate that Portugal may not achieve the targets of the Kyoto Protocol by increased use of biomass as fuels alone. In general, we may conclude that replacement of fossil fuels by biomass fuels like willow can be a step forward in reducing the emissions of greenhouse gases from the power sector. However, circumstances of biomass production determine to what extent emissions are reduced.

In terms of land needed for willow production, all the scenarios (baseline, 10% and 20%) seem to be possible to implement. The land requirements for willow production are less than 1% of agricultural or non-arable land in the baseline scenario. For the ten and twenty percent scenario, the area needed for willow cultivation on agricultural land would be about 2% and 4%, respectively, of the total area. If willow would be cultivated in non-arable land then it would require only about 1% of the non-agricultural area (10% scenario) or 3% (20% scenario).

If the soils need considerable fertilisation, like the case of the soils in Portugal, then there may not be many benefits of using willow for energy production. Other species, like Eucalyptus may be better adapted to the Portuguese soils and the use of this species for electricity production deserves attention. On the other hand, Portugal has large uncultivated areas (6.45 ha per 1000 ha) where the energy crops would be an interesting alternative.

5.2.2. The Netherlands

In The Netherlands, CO_2 emissions from power plants in the year 1990 amounted to 11.6 Mt C. Like in Portugal, most Dutch power plants are fossil-fuel based. In the baseline scenario emissions are calculated increase between 1990 and 2010. The increase ranges between 19% and 21% relative to 1990 for the different cases (Fig. 2). For the 10% and 20% scenarios either a decrease or increase of emissions is calculated, depending on the assumed growth conditions and fossil fuel replacement by willow. In the 10% scenario, emissions from electricity production are reduced relative to the baseline scenario by 2–8% (range for all cases), except when willow is grown according to the high cultivation case. When willow is grown on organic soils that receive high fertiliser inputs for 5 years, and yields are low, the greenhouse gas emissions from power generation may increase by about 5–8% when this willow is used to replace coal or natural gas in power plants. In the 20% scenario the Dutch emissions are 7–21% lower than the baseline scenario, in the no, low and average cultivation case and 14–21% higher in the high cultivation case.

The largest emission reductions are calculated for the 10% and 20% scenarios, assuming replacement of coal, while willow is grown in line with the average or below average cultivation case. The 20% scenario may be a promising option in terms of greenhouse gas emissions reduction for The Netherlands because in this scenario the 2010 emissions may not exceed the 1990 emissions, provided that willow is not grown according to the high fertilisation cultivation case.

For the amount of willow produced in the baseline scenario about 6% of the Dutch agricultural land and 5% of non-arable land would be required. These percentages are larger than for Portugal. In the 10% scenario willow cultivation would cover an area equivalent to 14% of the Dutch agricultural land and 12% of the non-arable land. In the 20% scenario these land requirements are even larger (29% of the agricultural land available). This may make the scenarios unrealistic, if the willow is to be grown within The Netherlands, even with efficient multifunctional land use schemes. On the other hand, the soils in The

Netherlands may be more suitable for the cultivation of willow than in Portugal, and they may need less fertilisation. This means that a reduction in the emissions from greenhouse gases may be achieved when willow replaces fossil fuels in Dutch power plants.

References

Abbasi, S., Abbasi, N., 2000. The likely adverse environmental impacts of renewable energy sources. Applied Energy 65, 121–144.

Alcamo, J., 2001. Scenarios as Tools for International Environmental Assessments. European Environment Agency, Copenhagen, Denmark.

Alcamo, J., Shaw, R., Hordijk, L. (Eds.), 1990, The RAINS Model of Acidification. Science and Strategies in Europe. Kluwer Academic Publishers, Dordrecht, The Netherlands.

Boyd, J., Christersson, L., Dinkelbach, L., 2000. Energy from willow—The Scottish Agricultural College, Swedish University of Agricultural Sciences, Netherlands Energy Research Foundation, Altener, DTI New and Renewable Energy Programme. The Scottish Agricultural College, Edinburgh, UK.

Dincer, I., 1999. Environmental impacts of energy. Energy Policy 27, 845–854.

Dones, R., Gantner, U., Hirschberg, S., 1998. Greenhouse gas total emissions from current and future electricity and heat supply systems, Fourth International Conference on Greenhouse Control Technologies, Interlaken, Switzerland.

Gupta, J., Vlasblom, J., Kroeze, C., Blok, K., Bode, J., Boudri, C., Dorland, K., Hisschemoller, M., 2002. An Asian Dilemma, Report no.: 410 200 097, The Netherlands, Free University of Amsterdam.

IAEA, 1998. Assessment of greenhouse gas emissions from the full energy chain of biomass. Papers presented at an Advisory Group Meeting organised by the International Atomic Energy Agency, Vienna, Austria, 16–19 December, 1997. International Atomic Energy Agency, Vienna, Austria.

IIASA, 2003. International Institute for Applied Systems Analysis, Laxenburg, Austria. RAINS website. www.iiasa.ac.at/˜rains.

IPCC, 1997. Revised IPCC Guidelines for National Greenhouse Gas Inventories, Intergovernmental Panel on Climate Change.

IPCC, 2001. Climate Change, Third Assessment Report, Intergovernmental Panel on Climate Change. Cambridge University Press, UK.

Kroeze, C., Mosier, A., 2000. New estimates for emissions of nitrous oxide. In: van Ham, J., Baede, A.P.M., Meyer, L.A., Ybema, R. (Eds.). Non-CO_2 greenhouse gases: scientific understanding, control and implementation. Kluwer Academic Publishers, Dordrecht, The Netherlands, pp. 45–64.

Kroeze, C., Mosier, A., Bouwman, L., 1999. Closing the global N_2O budget: a retrospective analysis 1500–1994. Global Biogeochemical Cycles 13 (1), 1–8.

Larsson, S., 2002. Full scale implementation of willow SRC (short rotation coppice) in Sweden, Agrobransle AB, Sweden.

Leemans, R., van Amstel, A., Battjes, C., Kreileman, E., Toet, S., 1996. The land cover and carbon cycle consequences of large-scale utilizations of biomass as an energy source. Global Environmental Change 6 (4), 335–357.

Londo, M., 2002. Energy farming in multiple land use—an opportunity for energy crop introduction in The Netherlands, Ph.D. Thesis. Utrecht University, Utrecht, The Netherlands.

Mosier, A., Kroeze, C., Nevison, C., Oenema, O., Seitzinger, S., van Cleemput, O., 1998. Closing the global N_2O budget: nitrous oxide emissions through the agricultural nitrogen cycle. Nutrient cycle in Agroecosystems 52, 225–248.

Nakicenovic, N., Davidson, O., Davis, G., Grubler, A., Kram, T., La Rovere, E., Metz, B., Morita, T., Pepper, W., Pitcher, H., Sankovski, A., Shukla, P., Swart, R., Watson, R., Dadi, Z., 2000. IPCC Special Report on Emissions Scenarios—Summary for Policymakers, Intergovernmental Panel on Climate Change, WMO and UNEP.

Nonhebel, S., 2002. Energy yields in intensive and extensive biomass production systems. Biomass and Bioenergy 22, 159–167.

Olesen, J., 2003. Energy crops as a strategy for reducing greenhouse gas emissions. Danish institute of agricultural sciences, Tjele, Denmark.

Streets, D., Waldhoff, S., 1999. Greenhouse gas emissions from biofuel combustion in Asia. Energy 24, 841–855.

Warburton, D., Robinson, R., Smith, C., 1997. Short rotation coppice for energy production—UK good practice guidelines, British Biogen, ETSU. Friends of Earth and Environmental Resolve, UK.