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Good or bad ethanol

– what determines this?

Pål Börjesson

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Title and subtitle

Good or bad bioethanol – what determines this?

Abstract

The purpose of this study is to describe how the energy efficiency and greenhouse gas (GHG) benefits of ethanol depend on local conditions and calculation methods. The following four parameters have been identified as crucial to the GHG benefits of ethanol: (i) energy efficiency and emissions of nitrous oxide during cultivation, (ii) what kind of fuel is used in ethanol plants, (iii) how efficiently by-products are utilised and their benefits credited, and (iv) the type of land used for cultivation.

To ensure that "good" ethanol is produced (with reference to GHG benefits), the following demands must be met:

- ethanol plants should use biomass and not fossil fuels
- cultivation of annual feedstock crops should be avoided on land rich in carbon (above and below ground), such as peat soils used as permanent grassland
- by-products should be utilised efficiently in order to maximise their energy and GHG benefits (and these benefits should be credited by system expansion, followed by economic allocation and physical allocation)
- nitrous oxide emissions should be kept to a minimum by means of efficient fertilisation strategies, and the commercial nitrogen fertiliser utilised should be produced in plants which have nitrous oxide gas cleaning

Current production of Swedish ethanol from wheat can be seen as "good" ethanol, reducing GHG emissions by some 80 % compared to petrol. Ethanol based on sugarcane from Brazil leads to a reduction of – on average – 85 %, while ethanol from maize in the USA leads to a reduction of only 20 % on average. The reason for this is that several ethanol plants in the USA are using coal (fossil fuel). There is potential for improvement of current ethanol production systems worldwide, leading to increased GHG benefits. On the other hand, increased competition for land in future may increase the risk of cultivation of annual ethanol crops on new farmland rich in carbon. This will reduce the GHG benefits of ethanol from annual crops. When such changes of land use are included in life cycle assessments of biofuels, complementary data should also be presented showing that this is the actual case regarding the specific biofuel production system analysed.

Keywords

Ethanol, biofuels, life cycle assessment, energy balance, greenhouse gases

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Foreword

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Pål Börjesson

Contents

1. Background

No-one has been able to avoid the debate raging over the past year in respect of biofuels, discussing whether these should be viewed as a threat or an opportunity. From the situation whereby biofuels were considered to be one of several vital solutions to the climate problem, the view put forward by the media has changed radically: now, the emphasis has been shifted to all the threats that could be posed. So which view is the true one? Well, the simple response is that both views could be true; there are both good and bad systems. Biofuels can be produced in so many different ways and in so many different locations in the world, and so conditions vary widely. It is not possible to generalise to the extent that the current media debate is pretending. To bring about a more varied discussion, as well as providing better decision data for various organisations, more knowledge needs to be developed and disseminated, and the various arguments for and against biofuels have to be reviewed critically.

Energy efficiency and climate benefits are two aspects often discussed in conjunction with sustainability and biofuels. Ethanol is currently the dominant biofuel on both a global and a national scale, which is why the debate often focuses on ethanol. In Sweden, the use of ethanol has increased over the past few years and now accounts for more than 3 % of fuel consumption for transportation by road. Most of this ethanol is imported, mainly from Brazil, while domestic ethanol from grain accounts for barely a fifth. On a global scale, the two dominant ethanol-producing countries today are Brazil (ethanol from sugarcane) and the USA (ethanol from maize). The most important factors dictating how “good” or “bad” ethanol is considered to be are how the production system is structured, what land is used to cultivate the plants and how the by-products generated are included. The results for the energy and climate performance of ethanol can vary extremely widely depending on what assumptions are attached to these factors.

2. Purpose

The purpose of this study is to describe the energy efficiency and climate benefits of ethanol and how these parameters are dependent on local conditions and calculation methodology. The emphasis is on Swedish ethanol based on grain, but links are also made to other production systems for ethanol. There is also some discussion of what potential there is for improvement in the production systems of today in respect of both the cultivation of raw materials and conversion of these into ethanol, along with when it is relevant to apply various calculation methods. There is also a comparison of the results with what are referred to as the “defaults” for ethanol proposed in the EU’s fuel directive. On the other hand, we have not included aspects such as the influence on biodiversity, working environment conditions, etc. as these aspects fall beyond the scope of this study. In other words, the definition of "good" and "bad" ethanol is limited here to include just the aspects of energy efficiency and climate benefits.

3. Structure of the production system

3.1. Cultivation of raw materials

Energy balance

Table 3.1 specifies the average energy balance for cultivation of grain for ethanol production in northern Europe. At present, around 4.2 MWh of primary energy per hectare and year is consumed in the form of fuel, manufacture of fertilisers, manufacture and maintenance of machinery, etc. A grain harvest is estimated on average to produce around 7.5 tonnes (15 % water content), which in energy terms corresponds to around 33 MWh; in other words, the energy balance is about 8. If the straw is also harvested, the energy harvest increases to around 55 MWh per hectare and the energy input to approximately 5.0 MWh, i.e. the energy balance is approximately 11. By way of comparison, the energy input of Brazilian sugarcane cultivation is estimated to be at around the same level per hectare as European grain cultivation (approximately 4 MWh/ha), while the energy harvest amounts to approximately 110 MWh; in other words, the energy balance amounts to more than 25 (Egeskog and Gustafsson, 2007). The cultivation of energy forest (such as salix) in northern Europe for cellulose-based ethanol production yields approximately 50 MWh per hectare and requires an energy input of approximately 2.5 MWh, giving an energy balance of approximately 20 (Börjesson and Tufvesson, 2008).

In future, it is estimated that the energy input in the case of grain cultivation could be reduced slightly thanks to more fuel-efficient tractors, more efficient cultivation of land, more energy-efficient fertiliser manufacture, etc. (see – for instance –Börjesson, 2007a; Jenssen and Kongshaug, 2003). This streamlining effort is being driven forward by the ever spiralling prices of diesel and energy, and it is estimated roughly that the energy inputs could be reduced by approximately 20 %. This will mean an increase in energy balance from the current value of around 8 to around 10 while the number of hectares harvested will remain unchanged. In parallel, there is also potential for increasing the grain harvest by cultivating more suitable wheat varieties for fuel production, for instance (see – for example –Börjesson, 2007a).

Table 3.1. Energy balance from grain cultivation[1]

Cultivation systems	**Energy harvest**[2]	**Energy input**[3]	**Energy balance**
	MWh/ha and year	*MWh/ha and year*	*Energy harvest / energy input*
Wheat – grain	33	4.2	8
Wheat – grain and straw	55	5.0	11

[1] Average for northern Europe, corresponding to cultivation in southern Sweden (Börjesson and Tufvesson, 2008).

[2] Grain harvest corresponds to 7.5 tonnes/ha (15 % water content) and straw harvest 5 tonnes/ha (15 % water content). The average wheat harvest is estimated to vary by approximately +/- 35 % between countries in north-western Europe (Ericsson and Nilsson, 2005).

[3] Relates to primary energy, including direct and indirect external energy inputs.

Greenhouse gases

Greenhouse gas emissions during cultivation are made up of carbon dioxide from tractors, fertiliser manufacture, etc. and nitrous oxide from arable land and from the manufacture of nitrogenous fertiliser. Often emissions of nitrous oxide contribute slightly more than emissions of carbon dioxide (see Table 3.2), but there is great uncertainty surrounding how much nitrous oxide is emitted by arable land, and such emissions may vary widely depending on local conditions. Here, emissions of nitrous oxide from land are estimated from the latest IPCC model (IPPC, 2006). Studies have also taken place which have used their own calculation methods. One example which received a lot of media attention was a study by Nobel Prizewinner Paul Crutzen et al. (2006), who asserted that biodiesel from rapeseed and ethanol from wheat and maize caused higher emissions of greenhouse gases than diesel and petrol due to high emissions of nitrous oxide during cultivation. However, this study was quickly queried by many land researchers, who demonstrated that Crutzen et al. used incorrect conversion figures for how efficiently crops absorb nitrogen, how much nitrogen recirculates in the ground and is available to form nitrous oxide, etc. These incorrect assumptions were probably due to misconceptions; and when these were corrected, Crutzen's results were approximately the same as those shown by the IPCC model, i.e. approximately a third as high (see – for example – Rauh, 2007; Ammann et al., 2007).

More fuel-efficient tractors, more efficient cultivation and manufacture of fertilisers, etc. can slightly reduce emissions of carbon dioxide per tonne of biomass, perhaps by up to 20 %. If, for example, biodiesel is used in tractors, emissions of carbon dioxide from these may be reduced by 50 % or more, depending on how this biodiesel is produced (see – for example – Börjesson and Tufvesson, 2008). In addition, nitrous oxide emissions may be reduced during the manufacture of nitrogenous fertiliser thanks to catalytic nitrous oxide gas cleaning, which is starting to be implemented in western Europe at the moment. Nitrous oxide emissions are being reduced by approximately 75 % in this way (Jenssen and Kongshaug, 2003). More efficient nitrogen utilisation during cultivation thanks to improved fertilisation strategies can reduce the risk of nitrous oxide formation in the ground.

Another factor which may be of great significance for the greenhouse gas balance is if cultivation involves a change in the use of land, which in turn leads to losses of land-based carbon. If, for example, straw is harvested, this slightly reduces the binding of land-based carbon (approximately 150 kg C/ha and year), and if grain starts to be cultivated on former grassland, the losses of soil carbon increase still further (approximately 500 kg C/ha and year) (Börjesson, 1999). In certain special cases, the losses of land-based carbon may greatly exceed other emissions of greenhouse gases, for example if grain starts to be cultivated on peat land which was previously used for cultivation of grassland. In these cases, the losses of soil carbon may amount to 7 tonnes C per hectare and year (see Table 3.2). However, changes to the land's carbon store in mineral soils are reduced over time, and after 30-50 years a new state of equilibrium can be attained. How long emissions of carbon dioxide take place from peat land depends on – among other things – the thickness of the peat layer, which in Sweden is estimated to amount to approximately 80 cm on average for cultivated peat soils (Börjesson, 1999). Stopping the cultivation of peat is thought to amount to approximately 1 cm per year when annual crops are cultivated, i.e. the losses of carbon would take place over approximately 80 years on average. Of total arable land in Sweden, 7-9 % is accounted for by cultivated peat land.

In the spring of 2008, two American studies were published in the scientific journal Science and received a lot of attention in the media (Searchinger et al., 2008; Fargione et al., 2008). Their results shows that it would take between 20 and 400 years for biofuels to become climate-neutral due to extremely high emissions of carbon dioxide from land and natural forest in connection with greater cultivation of energy crops. Thus these studies assumed that all production of biofuels requires new cultivation of farmland as all existing farmland is required for food production. The longest "payback time" related to biodiesel from palm oil from former rainforest peat land in Indonesia and Malaysia, and the shortest ethanol from sugarcane from the formerly afforested Cerrado in Brazil (Fargione et al., 2008). Losses of carbon dioxide from tropical peat land were estimated – for example – at 15 tonnes C per hectare and year and to continue over 120 years (the thickness of tropical peat soils was assumed to be 3 metres on average). An increase in the use of ethanol from maize in the USA was estimated to give a "payback time" of 167 years before the increased emissions of carbon dioxide from land and natural vegetation would be compensated by the reduction resulting from ethanol replacing petrol (Searchinger et al., 2008). Emissions of carbon dioxide from land (permanent grassland, forest land, etc.) and vegetation (such as forest) were estimated on average to amount to 12 tonnes C per hectare and year, i.e. land with large quantities of bound carbon were assumed to be cultivated. These estimates by Searchinger et al. are based on a global model relating to how an increase in the production of ethanol from maize in the USA is affecting the need for new cultivation both in the USA and in other parts of the world.

Cultivation of energy forest for cellulose-based ethanol gives lower emissions of greenhouse gases per MWh of biomass. If carbon dioxide emissions from altered land use are not included, emissions are estimated to amount to approximately 35 kg of carbon dioxide equivalents per MWh of salix chips. If cultivation takes place on former grain land, this leads to an increase in the binding of land-based carbon, which reduces emissions to under 10 kg per MWh of biomass (Börjesson and Tufvesson, 2008).

Table 3.2. Emissions of greenhouse gases in the case of grain cultivation, expressed as kg of CO_2 equivalents per MWh of harvested grain.[1]

Cultivation system	**CO_2 fossil fuels**[2]	**N_2O land**[3]	**N_2O N fertiliser manufacture**[4]	**Total**	**CO_2 change of land use**[5]	**Total**
Wheat – grain - cultivation on "normal" arable land	36	33	21 (6)	90	0	90
- cultivation on grass-covered mineral soil				90	40	130
- cultivation on grass-covered peat soil				90	750	840

[1] Average for northern Europe, which corresponds to cultivation in southern Sweden (Börjesson and Tufvesson, 2008). Excluding straw harvest.

[2] Emissions from tractors, manufacture of fertilisers, etc. Including a small quantity of methane emissions.

[3] Biogenic emissions from land based on the IPCC model (IPCC, 2006).

[4] Based on Jenssen and Kongshaug (2003) and Davis and Haglund (1999). Values in brackets relate to emissions from manufacture with catalytic nitrous oxide gas cleaning.

[5] In the case of straw harvest, the binding of land-based carbon is assumed to fall by 150 kg C/ha and year, and in the case of cultivation of annual crops on grass-covered mineral soil and peat soil, the losses of soil carbon are estimated to amount to 500 kg and 7000 kg C/ha and year respectively (Börjesson, 1999).

3.2. Transport of raw materials and products

The transport of raw materials and products to and from ethanol plants constitutes a minor part of the energy input in the case of ethanol production and so also makes a fairly marginal contribution to emissions of greenhouse gases. The energy input for the transport of grain and dried draff as a feed is estimated to correspond to approximately 5 % and 3 % respectively of the total energy input in the case of cultivation (Börjesson, 2007a). When straw is harvested, an energy input is required for straw transport which corresponds to approximately 15 % of the energy input in the case of cultivation. Emissions of greenhouse gases increase by just under half as much as emissions of greenhouse gases from cultivation consist of emissions of nitrous oxide (more than half), just under half being accounted for by carbon dioxide emissions from energy inputs of fossil fuels (see Table 3.2). The distribution of ethanol is assessed on average to involve an even lower energy input and even lower emissions of greenhouse gases despite the fact that the distance for transportation is normally longer. This is because ethanol has a considerably higher energy density than grain, draff and straw and so requires a considerably lower energy input per energy unit during transportation.

By way of comparison, the energy input for the transport by water of ethanol from Brazil to Europe is estimated to be equivalent to approximately the energy input required during sugarcane cultivation, constituting approximately 35 % of the total energy input in the case of sugarcane-based ethanol production (Egeskog and Gustafsson, 2007).

3.3. Running an ethanol plant

Energy balance

When fermenting grain to make ethanol, it is estimated that on average, approximately 55 % of the energy content of the grain is converted into ethanol, but this level of conversion may vary slightly depending on the structure of the process (see – for example – Börjesson, 2007b; Börjesson and Tufvesson, 2008). The input of external energy in the ethanol plant in the form of heat, steam and electricity is estimated to be equivalent to – on average – approximately 50 % of the energy content of the ethanol, when all energy inputs have been converted to primary energy (i.e. all losses in the respective fuel chain have been included). In this case too, there is variation due to the structure of the ethanol plant (Börjesson, 2007b; Börjesson and Tufvesson, 2008). From 2.3 kg (dry matter) of grain, we get one litre of ethanol and 0.8 kg (dry matter) of dried draff (also known as distiller's waste), as a by-product. Figure 3.1 summarises the energy flows (MWh per hectare and year) in the case of the manufacture of grain-based ethanol based on current production systems (including transportation).

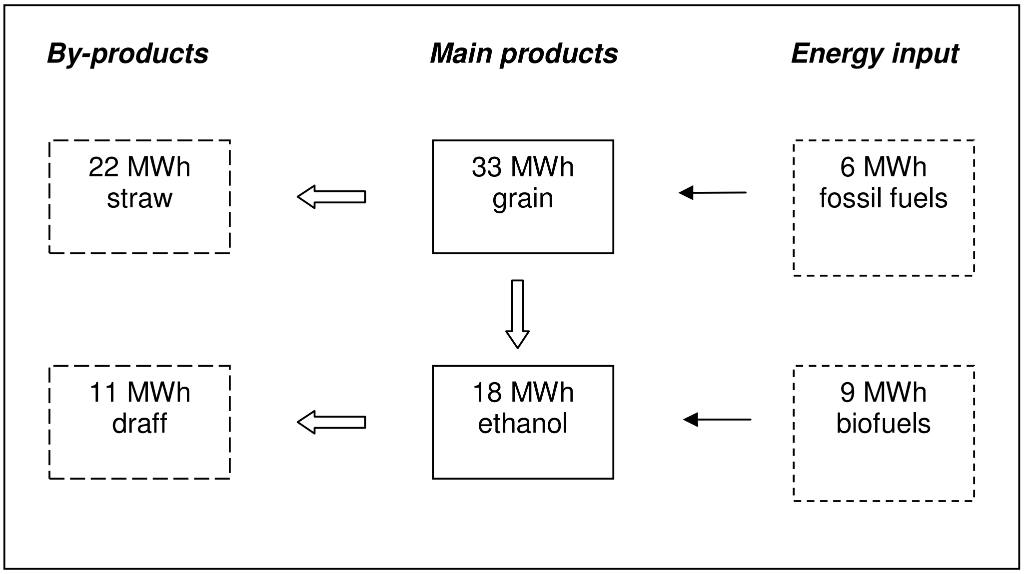

Figure 3.1. Energy flows in current production systems for grain-based ethanol in Sweden (Börjesson, 2007b; Börjesson and Tufvesson, 2008).

The yield of ethanol per hectare is estimated – on average – to amount to approximately 18 MWh; which, divided by the total energy input of approximately 15 MWh, gives an energy balance of approximately 1.2. If draff and straw are also included, the energy balance is 1.9 or 3.3 respectively, based on their energy content. Section 4 looks at various methods of distributing the energy input between ethanol, draff and straw; and the energy balance increases to more than 5 by means of what is known as system expansion. The energy balance for Brazilian ethanol from sugarcane is estimated to be around 8, excluding transport till Europe, or approximately 4.5 including transport when this is based on the energy content of the products (Egeskog and Gustafsson, 2007).

When fermenting wood raw materials to make ethanol, between 30 and 40 % of the energy content of the wood can be converted into ethanol, depending on which process technology is applied (Börjesson and Tufvesson, 2008). On average, one hectare if energy forest is estimated to be able to give approximately 18 MWh of ethanol, i.e. about the same amount as in the case of grain-based ethanol production. The input of external energy (on average approximately 13 % of the energy content of the ethanol, but this may vary slightly) is made up only of electricity when the need for heat and steam is met internally by the wood biomass. Besides ethanol, there is also a by-product in the form of lignin which is not required for internal energy production and which amounts to approximately 16 MWh per hectare (Börjesson and Tufvesson, 2008). The energy balance for ethanol based on energy forest amounts to approximately 3.7, excluding the by-product lignin, and just under 7 including this by-product.

Various kinds of energy streamlining may take place in future plants, leading to improved energy balances. For example, it is thought that more adapted integration between a power and heating plant and an ethanol plant could provide energy savings by allowing more optimal steam pressure to be utilised for the relevant processes and generation of electricity, better heat exchange and recovery of waste heat, along with integration of drying processes, etc. A cautious assessment is that it should be possible for the energy used in a developed ethanol plant to be 15 % lower than at present (Börjesson, 2007a). If local conditions are present with regard to access to district heating systems, any waste heat up to perhaps 20 % of the energy utilisation of the ethanol plant could be used as a basic load in district heating systems. Another type of streamlining involves increasing the exchange of ethanol per kg of grain by means of refinement. At present, the starch content is often around 70 % of the dry matter content, but with new ethanol wheat varieties this may be increased to up to about 75 %, which may increase the exchange of ethanol from 55 % up to approximately 58 % (Börjesson, 2007a). At the same time, the exchange of the by-product draff will be reduced slightly.

Greenhouse gases

How great emissions of greenhouse gases are from ethanol plants depends largely on what fuel is used to produce the heat, steam and electricity required for the manufacture of ethanol. In – for example – Swedish and Brazilian ethanol production, biofuels are used, so giving very low emissions of greenhouse gases, while in American and other European ethanol plants fossil fuels such as natural gas and coal are often used. Table 3.3 describes how great emissions of greenhouse gases from ethanol plants are depending on whether biofuel, natural gas or coal is used. As can be seen in Table 3.3, emissions from ethanol production account for less than 10 % of total emissions when biofuels are used in ethanol plants. When natural gas and coal are used, this amount increases to approximately 40 % and just under 60 % respectively. Apart from selecting biofuels instead of fossil fuels for ethanol production, streamlining can also lead to reductions in emissions of greenhouse gases, as discussed in preceding sections.

In the production of Brazilian ethanol from sugarcane, the by-product bagasse is used almost exclusively as an internal fuel in ethanol plants for production of the electricity and heat required. This means that life cycle emissions of greenhouse gases from ethanol from sugarcane originate mainly from cultivation of sugarcane and the transport of ethanol by sea to Europe. In the case of ethanol production from wood raw materials, by-products from the process are also used as internal fuel, i.e. this kind of production also results in marginal emissions of greenhouse gases.

Table 3.3. Emissions of greenhouse gases (kg of CO_2 equivalents per MWh of ethanol) from a grain-based ethanol plant depending on which fuel is used, plus total emissions when cultivation (and transport) are also included.[1]

Fuel in ethanol plant	**Cultivation**[2]	**Ethanol production**[3]	**Total**
Forest chips	170	10	180
Natural gas	170	110	280
Coal	170	210	380

[1] Based on Börjesson and Tufvesson (2008).

[2] Excluding straw harvest, the by-product draff and any changes of land-based carbon, i.e. all emissions of greenhouse gases load the ethanol alone (equivalent to 90 kg of CO_2 eq. / MWh wheat grain according to Table 3.2, which – including transport – gives just under 170 kg of CO_2 eq. / MWh of ethanol at an ethanol exchange of 55 %).

[3] The requirement for electricity and heat is met by means of power and heat production from the relevant fuel.

4. Calculation methodology for allocation to by-products

Apart from the fact that the structure of the production system has a great influence on the energy and environmental performance of the ethanol, the choice of calculation methodology also influences the results. As ethanol from – for example – grain and wood raw materials generates by-products, these also have to be taken into account when calculating the energy balance and emissions of greenhouse gases in order to give true and fair results. The ISO standard for life cycle assessment (ISO 14044) describes various calculation methods for dealing with situations when a production system generates several products (ISO, 2006). These methods are physical allocation, economic allocation and system expansion; and these are described in the following sections.

4.1. Physical and economic allocation

Figure 3.1 describes how much ethanol, draff and straw is provided by one hectare of grain in the form of energy. Section 3.3 also describes how the energy balance is altered when the energy input loads ethanol alone, both ethanol and draff, or ethanol, draff and straw. This is an example of physical allocation, i.e. the energy input is distributed between the various products on the basis of their energy content. One advantage of using physical allocation is that this is constant over time, i.e. the energy content in the products does not alter. One disadvantage of physical allocation is that this method can give far too "advantageous" results for the primary product (such as ethanol) if large quantities of by-products of considerably lower quality (such as straw) are also obtained. As can be seen in Figure 3.1, the quantity of straw acquired in the production system is greater than the quantity of ethanol from an energy standpoint; i.e. in the case of physical allocation, the straw has to bear the majority of the total energy input and emissions of greenhouse gases.

From an economic viewpoint, the value of ethanol is approximately 7 times higher than straw per energy unit on the basis of the current price level, and the price of draff is somewhere between. To achieve a fairer allocation of the energy input and emissions of greenhouse gases between ethanol, draff and straw, therefore, this can be based on the economic value of the products instead of physical allocation (known as economic allocation). However, one disadvantage of economic allocation is the fact that this changes over time as the prices of the various products are not constant. In the case of ethanol, draff and straw, however, it appears that the price levels for these three products have been linked relatively well over the past few years, which means that the basis for economic allocation has not altered to any great extent (Börjesson and Tufvesson, 2008).

Table 4.1 describes how an energy input and emissions of greenhouse gases load the various products in the case of grain-based ethanol production, depending on whether physical or economic allocation is applied. As can be seen from the table, the load on ethanol – for example – in the case of economic allocation is twice that in the case of physical allocation when straw is also included (70 % and 36 % respectively). If straw is not harvested, but just draff is acquired as a by-product, the corresponding difference is considerably less (79 % and 62 % respectively). In earlier life cycle analyses of biofuels, economic allocation is often used in preference to physical, based on the arguments specified above. However, when calculating the EU's "defaults" for biofuels, as they are known, it is suggested that physical allocation be used, but to "counteract" results that are too positive for grain-based ethanol, for example, by-products from cultivation are not included (i.e. straw in the case of ethanol production). According to the ISO standard, we should use both allocation methods if there is any doubt and show clearly how the choice of allocation method affects the result.

Major differences also result from allocation in the case of cellulose-based ethanol, depending on the calculation method. In the case of physical allocation, the load on ethanol is 52 % when the by-product lignin is assumed to be refined to form fuel pellets; and if economic allocation is applied, the load on ethanol increases to 77 % (Börjesson and Tufvesson, 2008). In the case of production of ethanol from sugarcane, allocation is relevant between ethanol and an excess of electricity which is not required internally within the process. The ethanol plant's electricity and heat requirement is produced internally by the by-product bagasse.

Table 4.1. Distribution of energy input and emissions of greenhouse gases between grain-based ethanol and its by-products in the case of physical and economic allocation respectively.[1]

Production system	**Physical allocation**[2] (%)	**Economic allocation**[3] (%)
Ethanol / draff (exc. straw harvest)	62 / 38	79 / 21
Ethanol / draff / straw (inc. straw harvest)	36 / 22 / 42	70 / 18 / 12

[1] Based on Börjesson and Tufvesson, 2008.

[2] Based on the energy content of the products.

[3] Based on the economic value of the products on the basis of the 2007 price level.

4.2. System expansion

One way of avoiding allocation in the case of life cycle assessment is to expand the system limits by also including the alternative products which the by-products will replace. The by-products' indirect energy and environmental benefits are included in this way in the total energy and environmental analysis and no allocations need to take place. The ISO standard for life cycle assessment (ISO 14044) recommends system expansion over physical and economic allocation as system expansion is deemed to give the truest, fairest results. Several life cycle assessments of biofuels also use this method in their analyses, such as the European well-to-wheel study – as it is known – produced by Concawe et al. (Concawe et al., 2007).

However, two important demands are made for system expansion to be possible: an alternative product to replace the by-product must be clearly identifiable, and there has to be reliable life cycle data for this alternative product. These demands often cannot both be met, which means that allocation has to be applied instead. Another limitation of system expansion is that the market for a by-product may be limited, and when this is saturated a new type of system expansion (or allocation) must be applied. This is applicable to the current market for draff as a protein feed in the case of milk and meat production as a substitute for imported soya protein from Brazil. In Sweden, this market is thought to be equivalent to ethanol production from grain of approximately 2-3 TWh per year, which corresponds to approximately 5 % of current petrol consumption (Börjesson, 2007b). Concawe's well-to-wheel study carries out a similar assessment of how large the market is for draff in Europe (Concawe et al., 2007). In the case of production of biodiesel from rapeseed, a by-product (rapeseed meal) is also acquired which is used as a protein feed for animal production; i.e. this production also has to be taken into account when assessing the market for draff.

As far as system expansion for the by-product straw is assessed, forest chips are thought to be the most realistic substitute fuel in Sweden as we still have unutilised potential for an increase in the extraction of forest fuels (Börjesson and Tufvesson, 2008). However, in other countries fossil fuels such as coal and natural gas may be the most realistic alternative fuels, which means considerably greater benefits from a climate viewpoint. There is also logic in assuming that mainly forest chips will be replaced with straw in Sweden, as we use forest chips as a fuel in current ethanol production but we could just as well use straw from the cultivation of grain for ethanol. This will lead to major energy benefits in the event of system expansion as the ethanol process can utilise internal straw fuel instead of external forest fuel.

As far as wood-based ethanol production is concerned, the substitute product for the by-product lignin is assumed mainly to involve wood pellets from fresh wood raw materials as dried residual products such as sawdust, shavings, sawmill chips, etc. are utilised fully at present (Börjesson and Tufvesson, 2008). The market for pellets is deemed to be very large in Europe, for example, and will not be limited for a long time. This system expansion means that energy benefits corresponding to 20 % of the energy content of the ethanol will be achieved, while at the same time reducing emissions of greenhouse gases.

Table 4.2 describes which indirect benefits are achieved when draff is used to replace imported soya protein as a feed and straw is used to replace forest chips as a fuel. The quality of draff as a protein feed is deemed to be slightly lower than soya meal; and this is why 1 kg of draff is assumed to be equivalent to 0.75 kg of soya meal and 0.25 kg of feed grain (Börjesson and Tufvesson, 2008). As can be seen from the table, substituting soya meal brings about major energy and climate benefits, while substituting forest chips brings about only marginal climate benefits but major benefits.

Table 4.2. Indirect energy and climate benefits when draff and straw are used to replace soya protein from Brazil and forest chips from Sweden. [1]

System expansion	**Energy invested** (MWh per MWh of ethanol)	**Emissions of greenhouse gases** [3] (kg of CO_2 equivalents per MWh of ethanol)
Draff replaces soya meal [2]	- 0.30	- 120
Straw replaces forest chips [3]	- 0.50	- 6

[1] Based on Börjesson and Tufvesson (2008).

[2] 1 kg of draff is assumed to be replaced by 0.75 kg of soya meal and 0.25 kg of feed grain, based on the protein content of the product. Life cycle data for imported soya meal is based on Flysjö et al. (2008).

[3] Straw is assumed to replace the forest chips used in the ethanol process for generation of electricity, steam and heat. Life cycle data for forest chips is based on Börjesson and Berglund (2007).

5 Crucial factors: a summary

The sections below describe a number of examples based on a summary of data presented in previous sections and illustrating the significance of various factors to the energy and environmental performance of ethanol, i.e. when “good” or “bad” ethanol is produced.

Energy balance

Figure 5.1 summarises the energy balance for grain-based ethanol production depending on the structure of the system and the calculation method for allocation to by-products. The energy balance for current systems amounts to approximately 1.2 when by-products are not taken into account (column 1), and 1.3 and 1.9 in the case of economic and physical allocation respectively to draff (columns 2 and 4). It is deemed possible to increase the energy balance from 1.2 to 1.5 by means of streamlining throughout the entire production chain when by-products are not taken into account (column 3). In future systems and when economic allocation to draff and straw takes place, the energy balance is approximately 2.4 (column 5). In current systems and when physical allocation to draff and straw takes place, the corresponding energy balance is 3.3 (column 6). When straw is taken into account as a fuel in the ethanol plant and draff is used to replace imported soya meal (i.e. system expansion), the energy balance is approximately 5.2 (column 7). When future streamlining potential is also included, the corresponding energy balance may increase to approximately 9 (column 8).

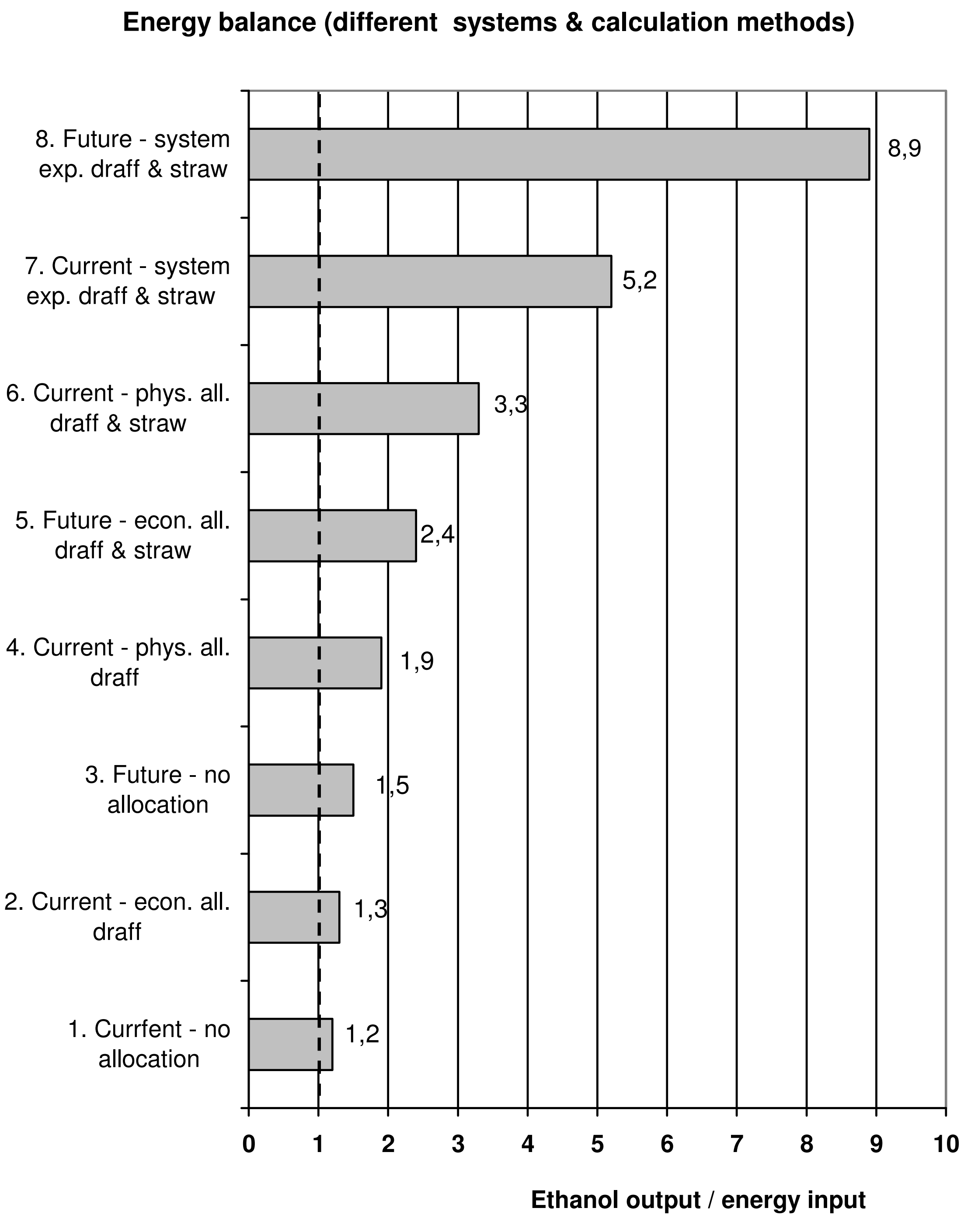

Figure 5.1. Energy balance for grain-based ethanol production, taking into account various system and calculation methods (see the text for more detailed explanations of each column) (processed data from Börjesson, 2007a and Börjesson and Tufvesson, 2008).

Greenhouse gases

Figure 5.2 summarises how emissions of greenhouse gases from grain-based ethanol production vary when changes of use of land and future potential for improvement are taken into account. There has been no allocation to by-products in the figure: all emissions load only the ethanol. The ethanol plant is assumed to use biofuel. More energy-efficient cultivation, catalytic nitrous oxide gas cleaning in nitrogenous fertiliser manufacture and improved nitrogen utilisation in cultivation are deemed to be potential ways of reducing emissions of greenhouse gases by approximately 25 % compared with present levels. If grain for ethanol starts to be cultivated on arable land which was previously used exclusively for cultivation of grassland, emissions of greenhouse gases may increase by 40-50 %. If grass-covered peat land starts to be used for cultivation of grain for ethanol, emissions of greenhouse gases will increase enormously, becoming 4-5 times higher than with petrol.

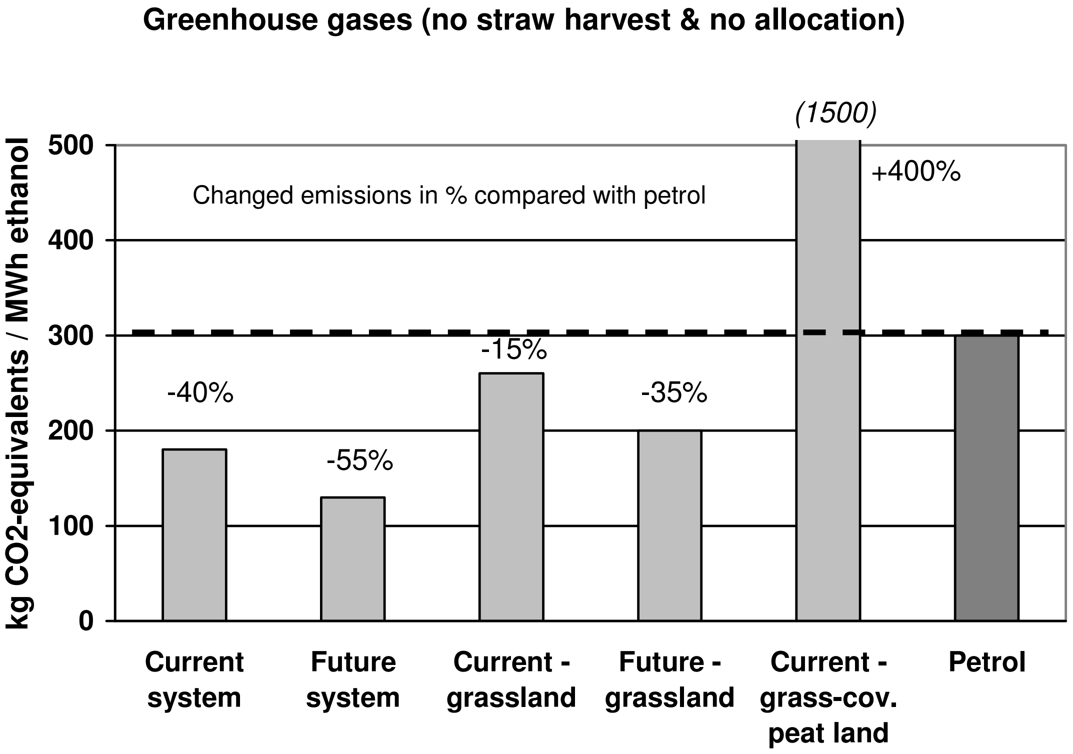

Figure 5.2. Emissions of greenhouse gases from grain-based ethanol production, taking into account potential for improvement and change of land use, and also in comparison with petrol. Note that all emissions load only the ethanol, i.e. straw is not harvested and there is no allocation to draff. The ethanol plant is assumed to use biofuel.

Figure 5.3 describes how emissions are affected by the fuel used in the ethanol plant. This figure does not include by-products. When natural gas is used instead of forest chips, emissions of greenhouse gases increase by 50-60 %; and if coal is used, the emissions double. When by-products are not taken into account, this means that emissions from ethanol are higher than emissions from petrol.

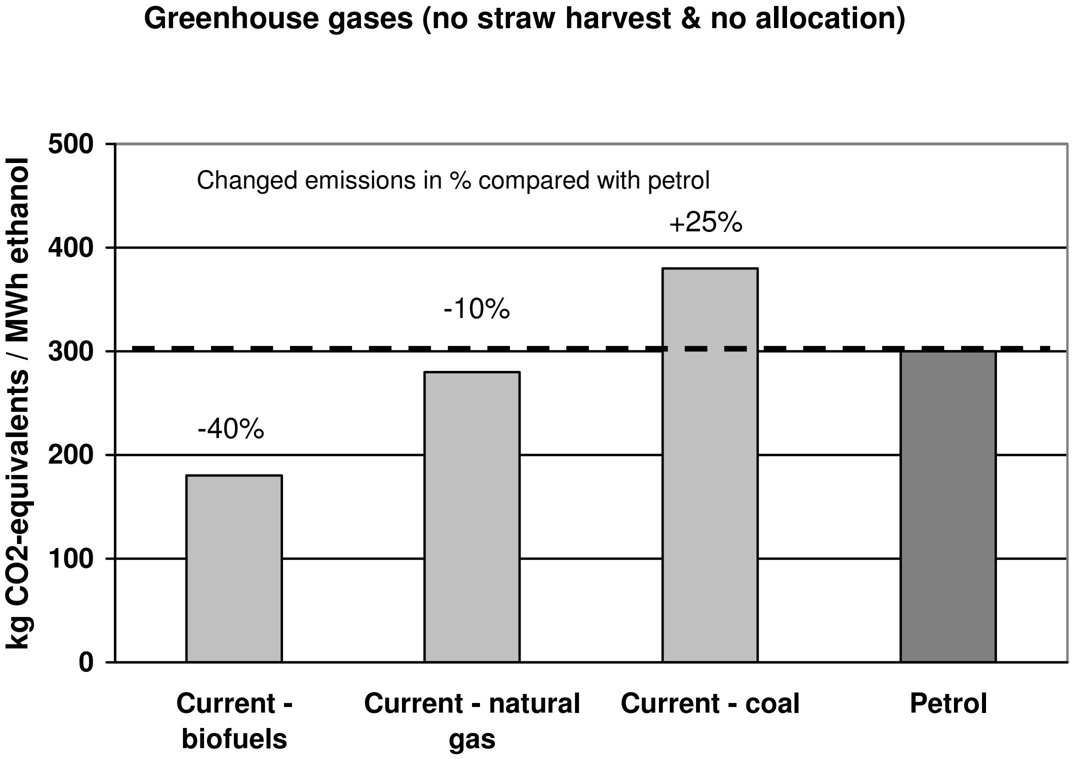

Figure 5.3. Emissions of greenhouse gases from grain-based ethanol production, taking into account which fuel is used in the ethanol plant and in comparison with petrol. Note that all emissions load only the ethanol, i.e. straw is not harvested and there is no allocation to draff.

Figure 5.4 describes how emissions of greenhouse gases change when the by-products draff and straw are also included and various allocation methods are applied. The greatest reduction is achieved when both straw and draff are included and allocation is based on the energy content of the products (physical allocation). In this case, emissions are reduced by approximately 65 %; and if only draff is included, the reduction amounts to approximately 35 %, compared with when no allocation takes place. When the allocation is based on the price of the product (economic allocation), the corresponding reduction amounts to approximately 30 % and 20 % respectively. Emissions of greenhouse gases from ethanol production are between 55 % and 80 % lower than with petrol in these cases.

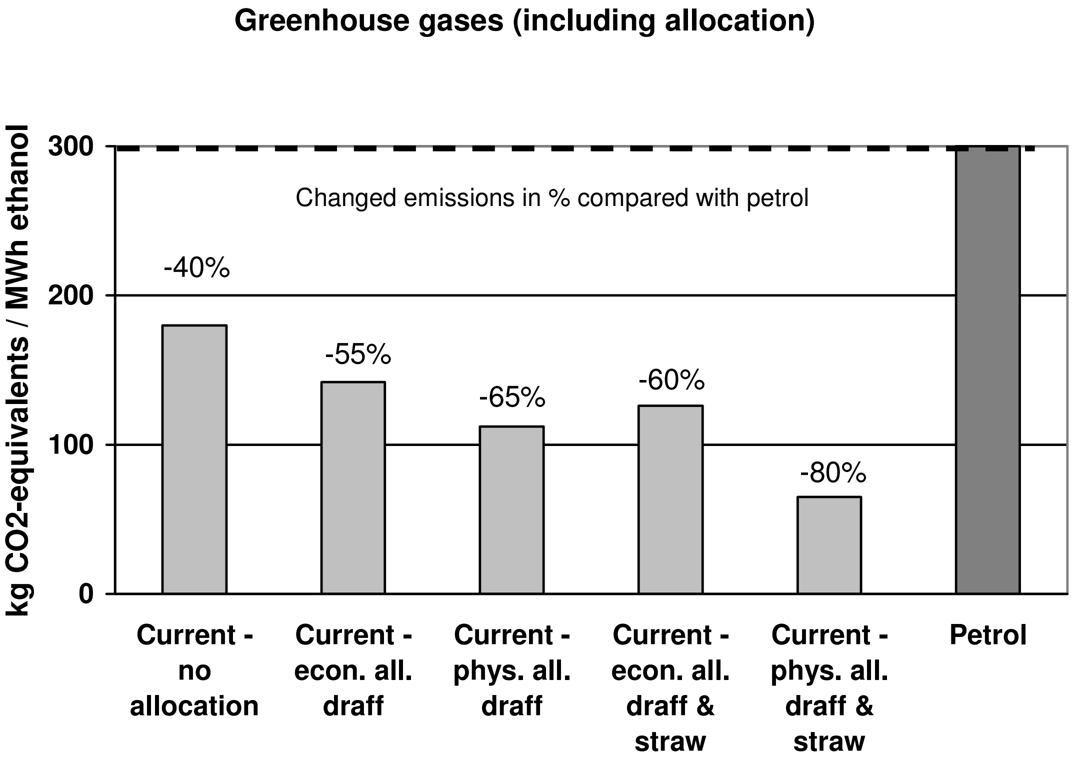

Figure 5.4. Emissions of greenhouse gases from grain-based ethanol production, taking into account the allocation method and in comparison with petrol. The ethanol plant is assumed to use biofuel.

Figure 5.5 describes how emissions of greenhouse gases change when what is known as system expansion takes place by assuming that draff is used to replace imported soya meal as a protein feed and straw is assumed to replace forest chips as a fuel. This ensures a great reduction in greenhouse gases, approximately 65-70 % compared with when no allocation takes place; mainly thanks to major indirect climate benefits when soya meal is replaced as a feed. However, the climate benefits are marginal when straw is assumed to replace forest chips as both are biofuels. Compared with petrol, ethanol emissions of greenhouse gases are 80-85 % lower when system expansion is applied.

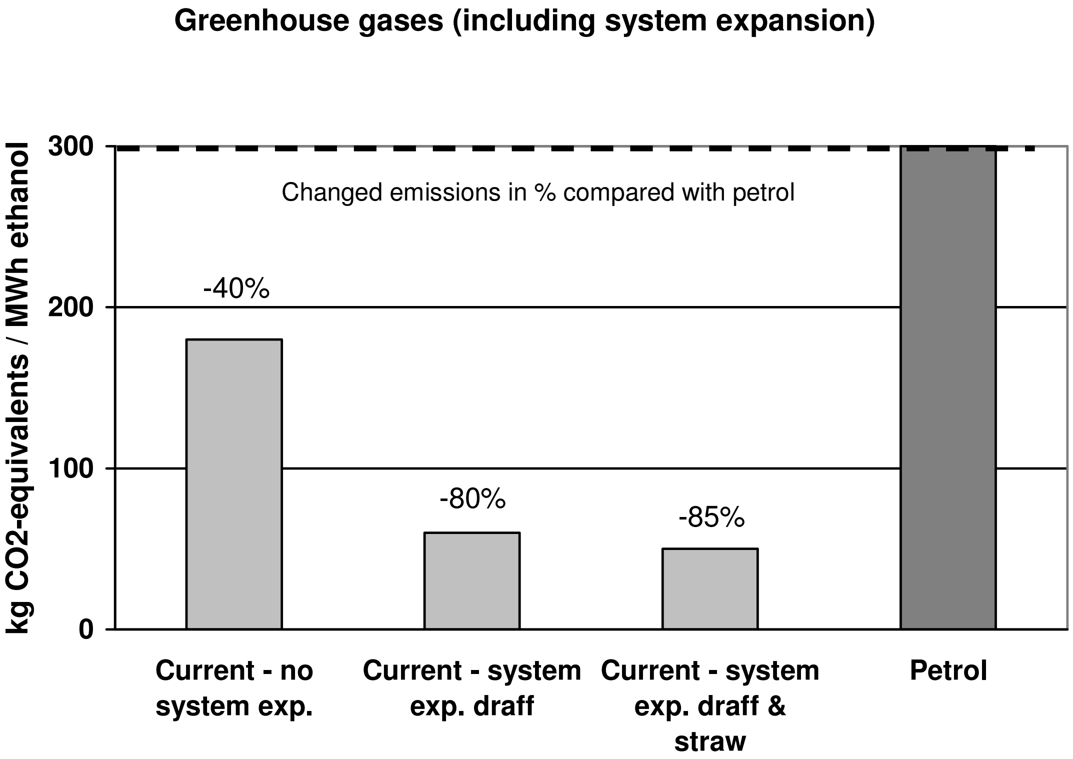

Figure 5.5. Emissions of greenhouse gases from grain-based ethanol production, taking into account system expansion and in comparison with petrol. The ethanol plant is assumed to use biofuel.

Figure 5.6. sums up the importance of all the different factors presented in Figures 5.2-5.5 and of significance as to whether ethanol should be considered "good" or "bad". Current ethanol production in Sweden can be said to lead to an 80 % reduction of greenhouse gases when biofuels are used in ethanol production and draff is used mainly to replace imported soya meal as a protein feed (column 2). However, there is potential for improvement which, together with straw harvesting, may result in even greater climate benefits compared with petrol (column 1). By way of comparison, current Brazilian ethanol from sugarcane is deemed to lead to an 85 % reduction when excess electricity from bagasse is included via system expansion (Concawe, 2007). When calculating what are known as "defaults" for biofuels within the EU's fuel directive, it is suggested that physical allocation be applied and that by-products from cultivation (such as straw) should not be included. This calculation method brings about a 65 % reduction for current ethanol production in Sweden (column 3), which is comparable with current EU proposals stating that biofuels should lead to at least 35 % lower emissions of greenhouse gases than is the case with fossil fuels.

If both straw and draff are taken into account and economic allocation is applied, the current production of grain for ethanol will lead to a 65 % reduction (column 4). In all of the above examples (columns 1-4), it is assumed that grain cultivation will take place on arable land where mixed plant cultivation takes place. If grain cultivation starts to take place on arable land where grass or grazing have been cultivated for a long time (several decades), current production systems for ethanol would lead to a 55 % reduction of greenhouse gases (column 5) instead of an 80 % reduction (column 2). All of the above examples are also based on the assumption that biofuels are used in the ethanol plant, but if this fuel is replaced with natural gas, the reduction will be 45 % (column 6) instead of 80 % (column 2).

When economic allocation of draff is applied instead of system expansion, and cultivation of grain for ethanol takes place on former grassland, the reduction of greenhouse gases will be approximately 25 % compared with petrol (column 7). If biofuels are replaced with coal in the ethanol plant and draff is assumed to replace soya meal, the reduction will amount to approximately 15 % (column 8). By way of comparison, the average reduction of greenhouse gases for American ethanol from maize is deemed to amount to around 20 % compared with petrol today, and this relatively limited climate benefit is due mainly to the fact that fossil fuels such as coal and – to an extent – natural gas are used in ethanol plants in the USA (Wang, 2007). However, there is major variation from more than a 50 % reduction to no reduction at all. Ethanol production from maize also gives a by-product which is used as an animal feed and is included in the above study by means of system expansion (Wang, 2007). In the European well-to-wheel study by Concawe et al. (2007), ethanol from grain is assessed to lead to a 70 % reduction of greenhouse gases compared with petrol when straw is used as a fuel in the ethanol plant. When natural gas is used, the reduction amounts to 45 %; and if brown coal is used, the emissions increase by approximately 10 %. The Concawe study also uses system expansion to include by-products.

According to Figure 5.6, ethanol production based on coal as a fuel and grain cultivation on former grassland is deemed to give higher emissions of greenhouse gases than petrol, irrespective of how by-products are included (columns 9 and 10). If grass-covered peat land is utilised for cultivation of grain for ethanol, this ethanol production leads to emissions of greenhouse gases 4-5 times higher than petrol (column 11). As discussed previously in section 3.1, Searchinger et al. (2008) and Fargione et al. (2008) have demonstrated, by way of model calculations, that ethanol leads to high emissions of greenhouse gases due to the fact that these suppress other cultivation (known as displacement) and that all biofuel production leads to new cultivation of land. Therefore, losses of carbon bound in biomass above and below ground are by far the largest source of greenhouse gas emissions in these model calculations. In addition, Searchinger et al. work on the basis that ethanol production from maize, excluding emissions from change of land use lead only to a 20 % reduction based on the current situation in the USA (see the reference to Wang, 2007). However, opinion is divided on how relevant the studies by Searchinger and Fargione are in the current situation as there is no clear evidence that biofuel production leads to a change of land use.

Biofuel production may also lead to increased binding of land-based carbon if this production is based on perennial crops such as energy grass and energy forest cultivated on marginal land with a low carbon content, or on arable land where annual crops have been cultivated. Ethanol production from energy forest is deemed, for example, to lead to a 75 % reduction of greenhouse gases when lignin pellets are included via economic allocation. If carbon binding in land is also included when perennial energy forest replaces grain, this reduction increases to between 90 and 95 % (Börjesson and Tufvesson, 2008).

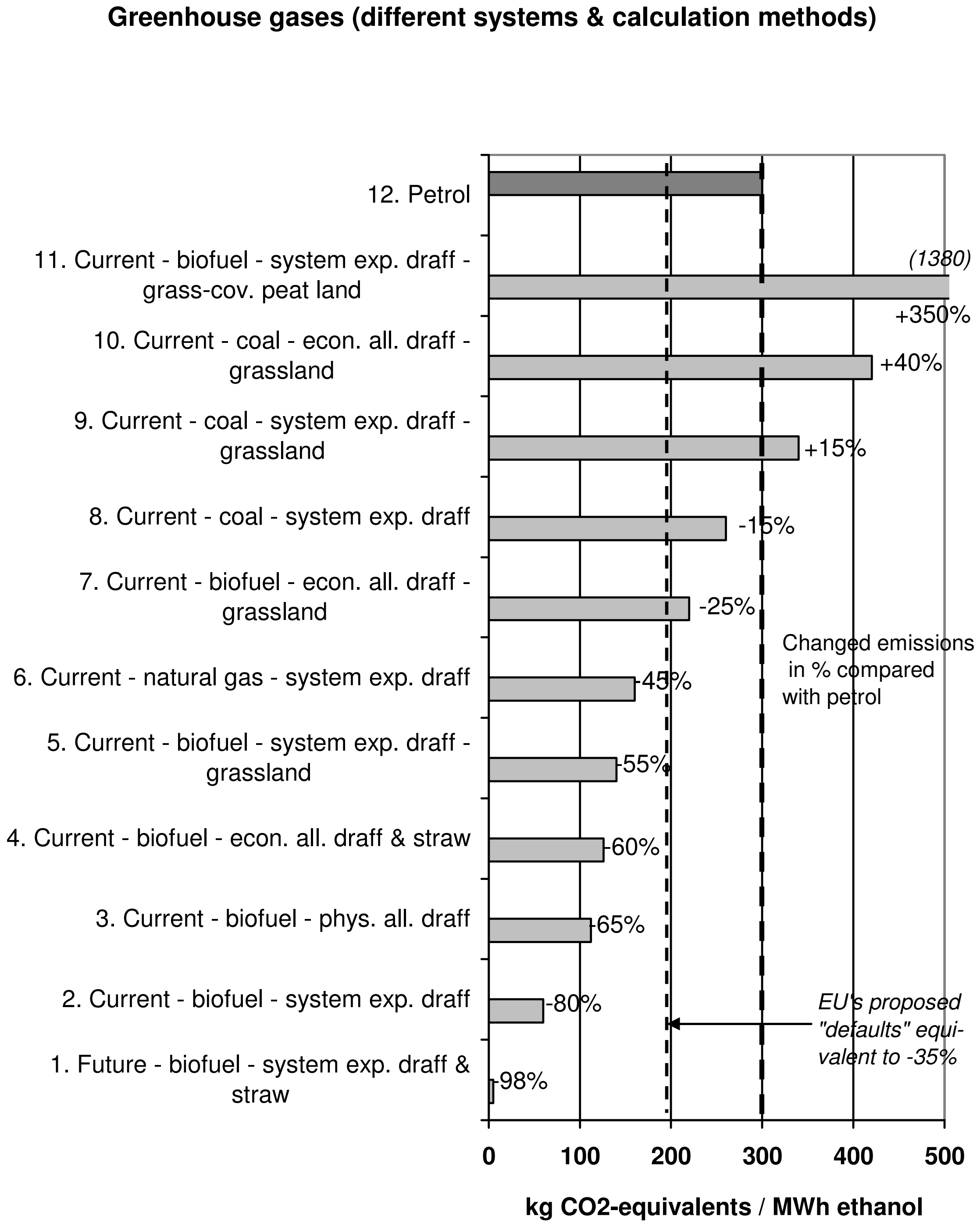

Figure 5.6. Emissions of greenhouse gases from grain-based ethanol production, taking into account various systems and calculation methods and in comparison with petrol and the EU's proposed "defaults" for biofuels. The various examples may be viewed as an illustration of the scale from "good" ethanol to "bad" ethanol (see the text for more detailed explanations of each column).

6 Conclusions and discussion

How climate-efficient ethanol is as a fuel is dependent largely on four factors: (i) cultivation efficiency and its emissions of nitrous oxide, (ii) which fuel is used in the ethanol plant, (iii) how efficiently by-products are dealt with and their benefits are credited, and (iv) what type of land is used for cultivation. Depending on these four factors, production systems for ethanol may mean anything from major climate benefits to increased emissions of greenhouse gases compared with petrol.

So to ensure that "good" ethanol is produced, the following demands may be made:

- ethanol plants must be run on biofuels, not on fossil fuels
- annual ethanol crops must not be cultivated on "carbon-rich" land which is not normally cultivated, or where perennial crops have been cultivated for a long time, such as grass-covered peat land
- by-products must be dealt with efficiently so that their energy and climate benefits are maximised (and we have to credit these benefits by means of system expansion wherever possible, and so economic allocation should be applied in preference to physical)
- emissions of nitrous oxide during cultivation must be kept to a minimum by means of more efficient nitrogen utilisation and use of nitrogenous fertiliser manufactured in plants with nitrous oxide gas cleaning

These days, Swedish ethanol from grain can be regarded as "good" because most of the demands above are met, leading to an approximately 80 % reduction of greenhouse gases compared with petrol. Possible improvements include dealing with straw more effectively and reducing emissions of nitrous oxide, both during cultivation and during the manufacture of nitrogenous fertilisers, as well as streamlining the entire production chain. This may mean that a reduction in excess of 90 % will be possible in future. On the other hand, emissions may increase slightly in future if grain for ethanol starts to be cultivated on ordinary mineral soil where grass has been cultivated for a long time, and when the market for draff as a protein feed is saturated and soya meal is not replaced (which may be the case when ethanol production corresponds to approximately 5 % of current petrol usage, which in turn will mean an eightfold increase in current domestic production). However, with a reduction in the provision of draff as feed, this can start to be used for production of biogas (which can also replace petrol), resulting in good climate benefits (see – for example – Börjesson and Mattiasson, 2007).

Brazilian ethanol from sugarcane can also be regarded as "good" ethanol at present because most of the demands above are met. The reduction of greenhouse gases is estimated at approximately 85 % compared with petrol. On the other hand, much of the American ethanol from maize can be regarded as "bad" because a lot of ethanol plants use coal as a fuel. In addition, the maize tops are not normally dealt with during cultivation. On average, current American ethanol from maize is deemed to lead to a 20 % reduction of greenhouse gases compared with petrol. If coal is replaced with biofuels, by-products will be handled more effectively and nitrous oxide emissions from maize cultivation will be reduced: ethanol from maize may even be regarded as "good" ethanol in future. It is thought that Swedish wood-based ethanol could lead to a 75 to 95 % reduction in greenhouse gases in future, depending on the system structure and calculation method.

The EU fuel directive proposes that biofuels should lead to at least a 35 % reduction in greenhouse gases (known as "defaults"). The calculation method proposed for the distribution of emissions between ethanol and by-products is physical allocation (i.e. based on the energy content of products), although this method is often deemed to give misleading results when large quantities of by-products of lower quality are achieved (such as straw). To compensate for this shortcoming, therefore, EU have opted not to include by-products from cultivation, and just to use by-products from the biofuel manufacturing process. With this calculation method, current Swedish grain-based ethanol will give a reduction in greenhouse gases of approximately 65 %.

The most relevant issue nowadays among environmental system researchers calculating the climate benefits of biofuels is whether or not it is relevant to include change of land use, which in turn leads to carbon dioxide flows in the carbon store in the land (and in any vegetation as well). As discussed previously, American studies based on economic models of global food production demonstrate that all biofuel production leads to change of land use and increased emissions of greenhouse gases compared with fossil fuels (see Searchinger et al., 2008). However, there are many researchers who query this simplified view and are of the opinion that there is a lot of untapped potential within existing cultivation land to increase the production of both food and energy. A very long-term excess of food (lasting several decades) and prices of agricultural products falling in real terms, the economic driving forces have been too weak to fully utilise all arable land and develop agricultural production. Therefore, current biofuel production is deemed to take place on land already cultivated for the most part. If changes to carbon stores in the land (and vegetation) are included in life cycle assessments of biofuels, we should demand that data be recorded at the same time which indicates that the relevant biofuel production does actually lead to change of land use.

To summarise: it is not possible to state generally whether ethanol is good or bad as regards the climate, as this is dependent upon the structures of the individual systems. Furthermore, there are various calculation methods which affect the results; i.e. we have to have a critical attitude towards the life cycle assessments which are published and which sometimes receive a lot of media attention. However, with our current knowledge we can point out the most important factors for whether or not ethanol production will lead to major climate benefits. This knowledge, together with supplementary knowledge on aspects such as influence on biodiversity, working environment conditions, etc., is important when structuring – for example – accreditation systems for biofuels so that we can make the correct demands and develop the good systems while at the same time avoiding the bad ones; i.e. allowing us to promote the development of “good” ethanol and counteract the production of “bad” ethanol.

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