Supergen Biomass and Bioenergy Consortium
Theme 6 Resource Assessment
Feedstock Properties

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Date of issue
August 2008
Contents

Contents ........................................................................................................................................... 3
1. Executive Summary ..................................................................................................................... 10
2. Introduction ................................................................................................................................. 21
2.1 Scope of assessment ................................................................................................................. 21
2.1.2 Selection of feedstocks ....................................................................................................... 21
3. Mechanically and Biologically Treated Waste (MBT) ............................................................ 24
3.1 Feedstock description .............................................................................................................. 24
3.2 Feedstock origin ...................................................................................................................... 24
3.3 Production ................................................................................................................................. 25
3.4 Economics ................................................................................................................................. 26
3.5 Environmental and ecological impacts .................................................................................... 26
3.6 Social context ........................................................................................................................... 29
3.7 Applications ............................................................................................................................ 31
3.8 Constraints ............................................................................................................................... 31
3.9 Conclusions ............................................................................................................................. 31
4. Waste vegetable oil ..................................................................................................................... 33
4.1 Feedstock description .............................................................................................................. 33
4.2 Production ................................................................................................................................. 33
4.3 Economics ................................................................................................................................ 36
4.4 Environmental and ecological impacts ................................................................................... 36
4.5 Social context ........................................................................................................................... 36
4.6 Applications ............................................................................................................................ 38
4.7 Constraints ............................................................................................................................... 38
4.8 Conclusion ................................................................................................................................. 38
5. Waste/recovered wood ............................................................................................................... 39
5.1 Feedstock description .............................................................................................................. 39
5.2 Feedstock origin ...................................................................................................................... 39
5.3 Economics ................................................................................................................................. 40
5.4 Environmental and ecological impacts .................................................................................... 40
5.5 Social context ........................................................................................................................... 41
5.6 Prospects and Status ............................................................................................................... 41
5.7 Feedstock description .............................................................................................................. 42
5.8 Feedstock origin ...................................................................................................................... 42
5.9 Economics ................................................................................................................................. 42
5.10 Environmental and ecological impacts .................................................................................. 42
5.11 Social context ........................................................................................................................ 43
5.12 Prospects and Status .............................................................................................................. 43
6. Straw ........................................................................................................................................... 44
6.1 Feedstock description .............................................................................................................. 44
6.2 Production ................................................................................................................................. 44
6.3 Economics ................................................................................................................................ 44
6.4 Environmental and ecological impacts .................................................................................... 44
6.5 Social context ........................................................................................................................... 45
6.6 Prospects and Status ............................................................................................................... 45
6.7 Feedstock description .............................................................................................................. 46
6.8 Feedstock origin ...................................................................................................................... 46
6.9 Economics ................................................................................................................................ 46
6.10 Environmental and ecological impacts .................................................................................. 46
6.11 Social context ........................................................................................................................ 47
6.12 Prospects and Status .............................................................................................................. 47
7.1 Feedstock description .............................................................................................................. 48
7.2 Feedstock origin ...................................................................................................................... 48
7.3 Technological issues associated with straw use ................................................................... 48
7.4 Environmental and ecological impacts ................................................................................... 48
7.5 Economics ................................................................................................................................ 48
7.6 Social context ........................................................................................................................... 49
7.7 Prospects and Status ............................................................................................................... 49
8. Forestry residues ......................................................................................................................... 50
8.1 Background ............................................................................................................................... 50
8.2 Feedstock description .............................................................................................................. 50
8.3 Feedstock origin ...................................................................................................................... 51
<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>13.5 Environmental and ecological impacts</td>
<td>69</td>
</tr>
<tr>
<td>13.6 Economics</td>
<td>69</td>
</tr>
<tr>
<td>14. Reed Canary Grass</td>
<td>70</td>
</tr>
<tr>
<td>14.1 Feedstock Description</td>
<td>70</td>
</tr>
<tr>
<td>14.2 Background</td>
<td>70</td>
</tr>
<tr>
<td>14.3 Feedstock Origin</td>
<td>70</td>
</tr>
<tr>
<td>14.4 Production</td>
<td>70</td>
</tr>
<tr>
<td>14.4.1 Yield</td>
<td>71</td>
</tr>
<tr>
<td>14.4.2 Environmental and ecological impacts</td>
<td>71</td>
</tr>
<tr>
<td>14.5 Economics</td>
<td>71</td>
</tr>
<tr>
<td>14.6 Environmental and ecological impacts</td>
<td>71</td>
</tr>
<tr>
<td>15. Marine Biomass</td>
<td>72</td>
</tr>
<tr>
<td>15.1 Introduction</td>
<td>72</td>
</tr>
<tr>
<td>15.2 Feedstock description</td>
<td>72</td>
</tr>
<tr>
<td>15.3 Production</td>
<td>72</td>
</tr>
<tr>
<td>15.3.1 Macro-algae</td>
<td>72</td>
</tr>
<tr>
<td>15.3.2 Micro-algae</td>
<td>73</td>
</tr>
<tr>
<td>15.4 Economics</td>
<td>74</td>
</tr>
<tr>
<td>15.4.1 Biomethane</td>
<td>74</td>
</tr>
<tr>
<td>15.4.2 Micro-algal biodiesel</td>
<td>74</td>
</tr>
<tr>
<td>15.4.3 Algal biohydrogen</td>
<td>74</td>
</tr>
<tr>
<td>15.5 Environmental and ecological impacts</td>
<td>75</td>
</tr>
<tr>
<td>15.5.1 Impacts – aquaculture and mariculture</td>
<td>75</td>
</tr>
<tr>
<td>15.5.2 Regulatory framework</td>
<td>78</td>
</tr>
<tr>
<td>15.6 Social context</td>
<td>80</td>
</tr>
<tr>
<td>15.7 Prospects/status</td>
<td>81</td>
</tr>
<tr>
<td>15.7.1 Biomethane</td>
<td>81</td>
</tr>
<tr>
<td>15.7.2 Bio-oil</td>
<td>81</td>
</tr>
<tr>
<td>15.7.3 Biodiesel</td>
<td>82</td>
</tr>
<tr>
<td>15.7.4 Algal biohydrogen</td>
<td>82</td>
</tr>
<tr>
<td>15.7.5 Conclusions</td>
<td>83</td>
</tr>
<tr>
<td>16. Oil seed rape</td>
<td>84</td>
</tr>
<tr>
<td>16.1 Feedstock description</td>
<td>84</td>
</tr>
<tr>
<td>16.2 Feedstock origin</td>
<td>84</td>
</tr>
<tr>
<td>16.3 Environmental and ecological impacts</td>
<td>85</td>
</tr>
<tr>
<td>16.3.1 Crop origin and growth pattern</td>
<td>85</td>
</tr>
<tr>
<td>16.3.2 Energy balance and greenhouse gas impact</td>
<td>85</td>
</tr>
<tr>
<td>16.3.3 Impact on habitat and biodiversity</td>
<td>86</td>
</tr>
<tr>
<td>16.3.4 Risks associated with agrochemical use</td>
<td>86</td>
</tr>
<tr>
<td>16.3.5 Impact on water courses – fertiliser and nitrates</td>
<td>87</td>
</tr>
<tr>
<td>16.3.6 Impacts on soil</td>
<td>87</td>
</tr>
<tr>
<td>16.3.7 Byproduct impacts</td>
<td>87</td>
</tr>
<tr>
<td>16.4 Production</td>
<td>88</td>
</tr>
<tr>
<td>16.5 Economics</td>
<td>90</td>
</tr>
<tr>
<td>16.6 Social context</td>
<td>90</td>
</tr>
<tr>
<td>16.7 Status and prospects</td>
<td>90</td>
</tr>
</tbody>
</table>
1. Executive Summary

A comprehensive evaluation has been carried out of 27 different indigenous and imported feedstocks with potential for UK bioenergy applications in the power, heat and transport sectors. The production process, occurrence and key physical and chemical properties are described as well as the likely end-use application and economic data, such as feedstock costs, where this was available. However, the main focus of the work is to assess the environmental, ecological and socio-economic impacts of utilising each feedstocks and the extent to which these or other factors might ultimately constrain the sustainable supply available in the UK.

Sustainable development requires a balanced consideration of environmental, social and economic impacts. Table 1.1 summarizes the most important technical, economic, environmental and social issues for the feedstocks considered. For some feedstocks there may not be any significant identified impacts within a category and, where this is the case, these have been left blank.

It is clear there are a large and diverse range of issues that need to be addressed within a broad sustainability framework. Many of the technical issues (such as fouling, corrosion and the need for adequate feedstock processing) are well known and can generally be managed with appropriate engineering and design precautions. Where these impact on efficiency or reliability, addressing these will also enhance economic and environmental sustainability. In addition establishing best practice for harvesting, processing, storage and transport of some feedstocks to make best use of the resource could improve the greenhouse gas balance for a number of production routes.

The key environmental issues range from a focus on emissions and supporting waste management strategies for wastes to concern about soil nutrient balances for residues and impacts on biodiversity, and hydrology for indigenous energy crops. Development of marine biomass in UK waters would result in a number of environmental issues that are not yet fully identified. As might be expected, the environmental issues associated with imported feedstocks are much more varied, depending on feedstock and region of origin. In many cases there are issues related to loss of habitat and deforestation with biodiversity and wider ecological consequences. With maize and soy there are specific issues related to genetic modification, where new species traits are resulting in higher or more indiscriminate use of agrochemicals. Agrochemical use, water use and effluent are particular issues, especially for sugar cane, which conversely has one of the most attractive greenhouse gas balances for ethanol production.

The social impacts of bioenergy development are even more diverse. With indigenous feedstocks issues tend to revolve around siting of facilities, employment and economic benefits. However the single biggest socio-economic issue for bioenergy is the potential for competition with production of food crops. This is particularly applicable where a food crop (such as wheat, maize or even sugar cane or oil seed crops) is being directly utilised to provide a feedstock for bioenergy. In such instances utilisation of the whole crop via advanced technologies is a critical development. But all feedstocks that are not wastes or residues compete for land and so augment food-fuel tension. Concerns arise when this increases food prices or infringes upon the capacity of local people to provide their own food. Many national governments have recognized the economic development opportunities offered by bioenergy crops for poorer farmers and communities and are implementing relatively
aggressive bioenergy development plans to avail of these. However the ability of these initiatives to actually deliver socio-economic benefits depends on how the growing industry is managed and the extent to which large-scale producers pass benefits down the supply chain and small scale producers are able to contract and engage with international buyers.

In some countries evidence of much more extreme social impacts are also emerging. Fundamentally bioenergy crops stand to benefit the landowner, by potentially increasing the income from and thereby the value of their land. This is obviously positive for landowners but makes the situation of tenant or permitted farmers much more precarious. In many countries conflicts between customary practices and legal rights in relation to land is resulting in ownership and usage disputes, which may lead to dispossession, intimidation, violence and other human rights abuses in the worst cases. There are also growing reports of the use of child labour, improper health and safety practices and other poor conditions for workers.

Many of the economic issues related to bioenergy revolve around competing uses for the feedstocks and comparison to prices of these. The most obvious is the potential for biomass crops to exacerbate increases in the prices of staple food commodities, such as wheat, maize or sugar. Other issues involve the requirement for developments to be large scale in order to compete on an international cost basis. A key issue here is the extent to which various policy mechanisms act to increase the demand and therefore the price for biofuels and how that impacts upon related markets.

The reason for bioenergy expansion is principally to address issues of global environmental (climate) change and resource depletion. However, taking steps towards these environmental objectives has other environmental and social consequences. The challenge is to ensure that bioenergy development takes place in a manner that minimizes negative environmental and social impacts. To do this requires decisions about what is considered an acceptable consequence of mitigating the very real environmental threat of climate change. These decisions depend acutely on values and priorities, which will vary for different stakeholders. So, the first challenge of sustainable bioenergy development is to develop some form of common vision of global sustainable bioenergy development. To date, this has been largely ignored at the expense of various national and pan-national strategies. The difficulty in agreeing this gives some indication of how difficult it would be for national governments and stakeholders to agree any sort of combined vision in this area. This is not helped by countries such as the UK declining to have any vision in favour of letting the market decide the optimal future for different technologies. Some degree of strategic leadership is essential, but currently lacking.

Assuming that agreement is possible and that a vision of what constitutes acceptable bioenergy development could be agreed we then encounter the challenge of turning this into reality. Fundamentally there is a need to reward responsible development consistent with the agreed vision and prevent development that is incompatible with agreed standards. To date the industry has turned to economic policy instruments to shape a market in which these objectives were nurtured. The crude principle is that by attributing financial premiums or rewards to “qualifying” bioenergy options we encourage those that are preferred. This has largely been done as a follow-up to successful initiatives to encourage renewable energy activities. Economic policy instruments such as tax incentives, green certificate schemes, quotas and obligations have been successful there and it has been assumed that a similar approach will work
for bioenergy e.g. the UK government’s response to the failure of the RO to incentivise dedicated biomass plant appears to be heading towards a solution of increasing the financial benefits, including via ROC banding that will particularly reward: dedicated biomass plant; fuels created using advanced conversion technologies; dedicated biomass with CHP; and dedicated energy crops with or without CHP1.

Economic policy instruments work well where we are rectifying a cost-benefit imbalance - e.g. we tax polluting behaviour to reflect external costs which the polluter does not have to pay directly, we reward renewable electricity to ensure that the saved carbon is valued as much as the electricity. However, it is impossible to place cost-benefit values on the myriad of different impacts that could be spawned by even a single bioenergy development. In this sense it may never be possible to create a market that actually reflects the true cost of bioenergy consumption. In the face of this problem policymakers have turned to the idea of certification, a form of regulation, as a means of ensuring sustainable bioenergy production.

There are a number of challenges inherent in going down the certification route. First of all, it should be clear from the above that any certification framework must be extremely wide in scope in order to capture the huge range of potential impacts of bioenergy. It must also account for differences in standards and acceptability across national boundaries. Second, there is the issue of cause and effect: in many cases bioenergy is not the cause of a problem but exacerbates it: e.g. land ownership and rights abuses are not solely the preserve of the bioenergy industry but are exacerbated by increasing the value of marginal land. Then there is the issue of displacement effects – human nature is such that if discrimination and child labour and other undesirable impacts were not being caused by bioenergy plantations they would probably be caused by an equivalent human activity. This is closely related to the fact that many of the impacts being blamed on the bioenergy industry are, in fact, illegal under national laws and international treaties. If this is going unchecked by national law enforcement agencies, then one could argue that there is little prospect of bioenergy accreditation schemes challenging it and little point in developing elaborate frameworks of checks where there is no practical way of policing them. On the other hand, one could argue that an adverse operational context does not justify wholly collaborating with the environmental and social abuses involved. Given market resources, it should be possible to establish some level of benign biomass supply, albeit at a considerably lower level than would be possible under unregulated conditions. Clearly there are very different opinions as to where, on this continuum from low regulation/ high supply to high regulation/low supply, the UK should position itself.

It is not obvious how a certification framework could be developed that would be able to fully and adequately address all of the issues raised in this report. It is even less obvious how it could be effectively policed. However, it is hoped, that in highlighting the diverse issues involved further consideration will be given to how these can best be addressed or accommodated. Within the framework of the Supergen bioenergy project the work presented here serves to elucidate the scope of the assessment that needs to be considered for bioenergy systems and is the first stage in the development of an appropriate assessment framework for comparative assessment of bioenergy

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sustainability. The aims of our assessment are somewhat different to those of the stakeholders and national authorities developing certification schemes. However, it is hoped that the work may assist in informing that process, where possible.
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<th>Feedstock</th>
<th>Technical</th>
<th>Environmental</th>
<th>Social</th>
<th>Economic</th>
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<tbody>
<tr>
<td>Mechanically and biologically</td>
<td>Corrosion, erosion and fouling impacting on reliability</td>
<td>Needs to be nested within a waste management</td>
<td>Site location and employee protection</td>
<td>Policy incentives required</td>
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<td>and treated waste (MBT)</td>
<td></td>
<td>framework with strong recycling objectives</td>
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<tr>
<td>Waste vegetable oil [1]</td>
<td>Well understood and commercialised conversion process</td>
<td>Greenhouse gas balance can be attractive and waste</td>
<td>Currently has public appeal, but quality control needed to maintain this</td>
<td>Subsidy to protect from competing feedstocks may be critical (especially imported biodiesel price)</td>
</tr>
<tr>
<td>Waste wood</td>
<td>Separation of uncontaminated wood stream</td>
<td>Emissions control for treated wood, including</td>
<td>Separation of wood waste by users</td>
<td>Cost of separation e.g. at civic amenity sites</td>
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<td></td>
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<td>compliance with Waste Incineration Directive where</td>
<td>Airborne pollutants from new facilities</td>
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<td></td>
<td></td>
<td>appropriate</td>
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<tr>
<td>Poultry litter</td>
<td>Potential for fouling/slagging</td>
<td>Airborne emissions</td>
<td>Location of new facilities</td>
<td>Alternative disposal (land-spreading) is low cost</td>
</tr>
<tr>
<td>Straw</td>
<td>Potential for fouling, slagging and corrosion</td>
<td>Airborne emissions</td>
<td>Location of new facilities</td>
<td>Relatively high feedstock cost (£20-25/t)</td>
</tr>
<tr>
<td>Forestry residues</td>
<td>Residue harvesting not well demonstrated</td>
<td>Impact of removal on future soil quality</td>
<td>Rural employment potential by improved woodland management</td>
<td>Relatively expensive at 58-120 euro/odt &amp; competing markets</td>
</tr>
<tr>
<td>Forestry-related (arboricultural</td>
<td>Physical processing</td>
<td>Airborne emissions</td>
<td>Location of new facilities</td>
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<td>arisings and sawmill co-product)</td>
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<tr>
<td>Pellet production</td>
<td>Requires dry uniform starting material</td>
<td>Production uses 10% of embodied energy</td>
<td>More user-friendly biomass product</td>
<td>May be cheaper to import to UK from European producers</td>
</tr>
<tr>
<td>Short rotation coppice</td>
<td>Wood comminution, drying &amp; storage</td>
<td>Positive impact on biodiversity, but potential</td>
<td>Rural diversification</td>
<td>70 euro/odt commonly achieved in England, at which price positive margins can be achieved</td>
</tr>
<tr>
<td>Short rotation forestry</td>
<td>Lack of practical UK experience</td>
<td>Biodiversity, hydrology, landscape</td>
<td>A long term commitment</td>
<td>Not as economically viable as SRC at present</td>
</tr>
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<td>Feedstock</td>
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<td>Economic</td>
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<tr>
<td>Switchgrass</td>
<td>Can be difficult to establish</td>
<td>Benefits pheasants, quail &amp; rabbits</td>
<td>Little known crop</td>
<td>Attractive production cost: £30-57/odt</td>
</tr>
<tr>
<td>Reed canary grass</td>
<td>Robust perennial grass but UK yields have been disappointing</td>
<td>Few significant issues identified to date, drought tolerant</td>
<td>Little known crop</td>
<td>Poor, unpredictable yields to date, impacting on economics</td>
</tr>
<tr>
<td>Marine biomass</td>
<td>High mineral, metal, halogen and ash content</td>
<td>Environmental impact of UK wild harvest and inshore cultivation likely to limit supply</td>
<td>May be of development and energy security value to rural coastal communities</td>
<td>Use of residues from non-fuel macro-algae processing or cheaper imported macro-algae may be most cost-effective</td>
</tr>
<tr>
<td>Oil seed rape</td>
<td>Only grown every 3-4 yrs in rotation</td>
<td>Relatively high N fertiliser inputs &amp; leaching risk</td>
<td>Competes with food crops – could impact on prices</td>
<td>Little international trade; rape seed meal could influence livestock feed production/prices</td>
</tr>
<tr>
<td>Wheat</td>
<td>Challenge is to use whole crop (2nd generation)</td>
<td>Greenhouse gas savings need enhancing</td>
<td>Significant potential to impact on world food prices</td>
<td>UK high yielding but also high production costs</td>
</tr>
<tr>
<td>Jatropha</td>
<td>High yield and well established processing methods but optimisation for nitrogen and irrigation need investigation</td>
<td>Can grow in arid, poor soil, but with relatively low oil yield. May result in forest destruction or land theft if preferentially yielding sites are chosen and local access rights ignored</td>
<td>Has potential to assist rural poor in developing countries, but local benefits likely to be influenced by land ownership and working conditions</td>
<td>Minimum plantation size of 200 ha for economic viability Heavy investment by D1 and BP underway</td>
</tr>
<tr>
<td>Maize</td>
<td>Poor (USA) but improving greenhouse gas balance</td>
<td>Genetic modification Low GHG saving</td>
<td>Food-fuel competition</td>
<td>Reducing feedstock price in face of rising mineral oil price</td>
</tr>
<tr>
<td>Palm Oil</td>
<td>Energetically efficient but little success in achieving yield increases</td>
<td>Deforestation and peatland drainage Loss of habitat for rare species</td>
<td>Labour intensive with significant employment potential supporting local economies Significant source of land tenure conflict in Indonesia</td>
<td>Lowest cost vegetable oil in absence of subsidies (cheap land and labour)</td>
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<td>Feedstock</td>
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<tr>
<td>Palm Kernel Expeller</td>
<td>As for palm oil</td>
<td>As for palm oil</td>
<td>As for palm oil</td>
<td>Recent sharp increases to $120/t</td>
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<tr>
<td>Soy</td>
<td>Increasing resistance of GM soy to agrochemicals</td>
<td>Future expansion likely in regions of high biodiversity and endemism</td>
<td>Large scale production leads to fewer jobs, narrower consolidation of profits and land-rights issues, Intensive use of agrochemicals leading to environmental pollution</td>
<td>High food value makes soy biodiesel production economically challenging; conversely biodiesel demand is exacerbating high price</td>
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<td>Sugar cane</td>
<td>Well understood and commercialised process, assisted by breeding and other research programmes</td>
<td>Loss of natural habitats, intensive use of water, heavy use of agrochemicals, discharge and runoff of polluted effluent, air pollution.</td>
<td>Can be poor working conditions: chemical and pesticide use, cane burning, Exploitation and intimidation common. Displacement of rural farmers and concentration of land ownership.</td>
<td>Currently Brazilian sugar cane ethanol is 50% cheaper per litre of gasoline equivalent than US corn ethanol</td>
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<td>Sweet sorghum</td>
<td>Well adapted to marginal lands</td>
<td>Requires irrigation</td>
<td>Farmers' perception positive as resembles sugar cane/corn</td>
<td>No new equipment required for cultivation</td>
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<td>Very high yield (3-4 fold higher than wheat, corn)</td>
<td>Can complement sugarcane in certain regions (e.g. Africa) in terms of growing period within a year</td>
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<td>High yields within short growing period (120-170 days)</td>
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<td>High yield makes it very cost effective</td>
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<td>Cynara cardunculus</td>
<td>High yield biomass &amp; oil; difficult ash properties</td>
<td>Can protect against soil erosion</td>
<td>Viewed positively by farmers; easy to cleared</td>
<td>Established from seed – low production costs</td>
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<td>Olive residues</td>
<td>Sodium and chlorine leading to slagging, corrosion; some milling</td>
<td>Loss of soil nutrients; airborne emissions from combustion</td>
<td>Public concerns over siting of new facilities</td>
<td>Low cost waste; large UK imports but no established global trade</td>
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<td>Ethanol</td>
<td>Issues are feedstock-specific</td>
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Table 1.2 identifies one or more key constraints which the authors consider has most potential to limit the supply of this particular feedstock to the UK. Where possible this has been accompanied by an indicative estimate of the likely resultant resource. Detailed calculations of resource estimates are generally beyond the scope of this report; and so these figures should not be relied upon other than as an indicative, order of magnitude estimate.

Table 1.2: Key constraints relevant to selected feedstocks

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<thead>
<tr>
<th>Feedstock</th>
<th>Key constraint(s) on maximum resource quantity</th>
<th>Indicative quantities</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mechanically and biologically treated waste (MBT)</td>
<td>Social acceptability of energy recovery facilities</td>
<td>10 Mtpa, including existing 2.8 Mtpa incinerated</td>
</tr>
<tr>
<td>Waste oil</td>
<td>Practicalities of collection</td>
<td>Currently ~100,000 tpa collected; could be up to 10 times this if domestic collection fully implemented</td>
</tr>
<tr>
<td>Waste wood</td>
<td>Practicality and cost of separating wood waste stream</td>
<td>6.6 Mtpa at CA sites each year, increasing at 6% pa</td>
</tr>
<tr>
<td>Poultry litter</td>
<td>Only viable where sufficient geographical litter density</td>
<td>Poss 2 plants (100-500 ktpa each, total 75 MWe max)</td>
</tr>
<tr>
<td>Straw</td>
<td>Only viable where straw economically available</td>
<td>9-10 Mtpa produced; 3 Mtpa available in eastern counties</td>
</tr>
<tr>
<td>Forestry residues</td>
<td>Regional economic viability</td>
<td>800,000 tpa allowing for competing uses</td>
</tr>
<tr>
<td>Forestry-related material (arboricultural arisings and sawmill co-product)</td>
<td>Competing uses</td>
<td>340 ktpa arboricultural, 86 ktpa sawmill co-product (allowing for competing uses)</td>
</tr>
<tr>
<td>Pellet production</td>
<td>Processed form of material dealt with elsewhere in this work</td>
<td>No new additional resource (existing UK production capacity)</td>
</tr>
<tr>
<td>Short rotation coppice</td>
<td>Land availability</td>
<td>5% of UK arable land (4.4 Mha) would give approx. 2.2 Mtpa</td>
</tr>
<tr>
<td>Short rotation forestry</td>
<td>Land availability</td>
<td>No real existing UK experience</td>
</tr>
<tr>
<td>Switchgrass</td>
<td>Land availability</td>
<td>No real existing UK experience</td>
</tr>
<tr>
<td>Reed canary grass</td>
<td>Land availability</td>
<td>No real existing UK experience</td>
</tr>
<tr>
<td>Marine biomass</td>
<td>Economic viability</td>
<td>No substantial UK experience</td>
</tr>
<tr>
<td>Oil seed rape</td>
<td>Rotational position</td>
<td>500,000 ha with 50% expansion based on projected biodiesel plans</td>
</tr>
<tr>
<td>Wheat</td>
<td>Competition with food uses</td>
<td>Around 2 Mha in Uk for wheat production but mostly food; small amount distilling</td>
</tr>
<tr>
<td>Jatropha</td>
<td>Land availability/ investment capital</td>
<td>Existing (India 500,000ha, China 2Mha, Malawi 200,000 ha) @ 3000 l biodiesel/ha Planned: tens of millions of hectares: India, China, western &amp; southern Africa, Asia</td>
</tr>
<tr>
<td>Maize</td>
<td>Price</td>
<td>US production dominates</td>
</tr>
<tr>
<td>Palm Oil</td>
<td>Land &amp; competing markets (only 1% of palm oil currently goes into biodiesel production)</td>
<td>Currently 9.86 Mha (Malaysia/Indonesia) @3.74 t/ha/yr</td>
</tr>
<tr>
<td>Palm Kernel Expeller</td>
<td>Palm oil production</td>
<td>2.1 MT from Malaysia in 2005 0.4t PKE/ha pa</td>
</tr>
<tr>
<td>Feedstock</td>
<td>Key constraint(s) on maximum resource quantity</td>
<td>Indicative quantities</td>
</tr>
<tr>
<td>--------------------</td>
<td>-----------------------------------------------</td>
<td>---------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Soya</td>
<td>Land availability in Latin America and competition with food market</td>
<td>Global increase of 40% by 2020 before biodiesel demands considered</td>
</tr>
<tr>
<td>Sugar cane</td>
<td>Land availability/investment capital</td>
<td>Little commercial production, but trials in China, USA &amp; elsewhere</td>
</tr>
<tr>
<td>Sweet sorghrum</td>
<td>Not suitable for growth in UK and pre-processing &amp; transport not well established</td>
<td></td>
</tr>
<tr>
<td>Cynara cardunculus</td>
<td>Need for specialized harvesters</td>
<td>Spain, Greece &amp; Italy are main producers; Extemadura (NW Spain) produces 590 ktpa @20 odt/ha pa</td>
</tr>
<tr>
<td>Olive cake</td>
<td>Olive production</td>
<td>5 Mt produced worldwide (0.8t residues per t oil) and 283 kt imported to UK in 2006 for cofiring</td>
</tr>
</tbody>
</table>
| Ethanol            | Availability of a sustainable product on international market | 1. USA 18,400 Ml  
2. Brazil 17,000Ml  
3. China 3,800 Ml  
4. India 1,900 Ml  
(UK 12th 280 million litres) |

An important part of theme 6 work involves assessment of the social aspects of UK bioenergy systems and this incorporates engagement with a variety of stakeholders relevant to the industry and recording of their opinion and attitudes towards different feedstocks. This work is in early stages; however, it is appropriate in an assessment of this sort to attempt to give some early indication of stakeholder perceptions of different feedstocks. Table 1.3 therefore attempts to summarize key stakeholder views in relation to some of the feedstocks studied. These have been obtained via a combination of direct consultation as part of this research work and scrutiny of publicly available material.

For further detail on any of these areas the reader is referred to the relevant section of this report. It should be noted that this is an early output of a project and so lack of comment or data does not imply that it is unimportant, unless specifically stated so.
<table>
<thead>
<tr>
<th>Feedstock</th>
<th>Selected stakeholder views</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mechanically and biologically treated waste (MBT)</td>
<td>May be seen as ‘green’ if facilitates materials recovery but has been contentious&lt;br&gt;Local authority opinion likely to be critical</td>
</tr>
<tr>
<td>Waste oil</td>
<td>Doesn’t compete with food production or cause land use change</td>
</tr>
<tr>
<td>Marine biomass</td>
<td>Substantial wild harvesting likely to be of major concern and/or prohibited&lt;br&gt;Visual and ecological impact of large scale cultivation likely to be of concern</td>
</tr>
<tr>
<td>Oil seed rape</td>
<td>Intensive cultivation of set aside/fallow land likely to be contested</td>
</tr>
<tr>
<td>Jatropha</td>
<td>Rural development and environmental potential may only be realised (if only partially) if existing land rights are honoured, and if inputs (good quality land, water and fertiliser) are low&lt;br&gt;Disputes over definition of ‘wasteland’ and marginal land</td>
</tr>
<tr>
<td>Maize</td>
<td>Objection to:&lt;br&gt;GM maize&lt;br&gt;Low GHG saving&lt;br&gt;Use of edible feedstocks&lt;br&gt;Use of prime agricultural land&lt;br&gt;Use instead of transport demand management&lt;br&gt;Acceptance for second generation technologies should not be presumed: arable land still used for fuel</td>
</tr>
<tr>
<td>Sugar cane</td>
<td>High level of GHG savings seen as positive&lt;br&gt;Direct and indirect land use change seen as negative&lt;br&gt;South American labour conditions could become a more significant issue for European critics</td>
</tr>
<tr>
<td>Ethanol</td>
<td>Issues are feedstock-specific</td>
</tr>
</tbody>
</table>
2. Introduction

2.1 Scope of assessment
This report is an early output of theme 6 of the refunded EPSRC Supergen Biomass and Bioenergy Consortium, which runs from 2007-11. The report consists of an overview of the properties of bioenergy feedstocks of potential value in future UK bioenergy scenarios. The overview is not intended to be comprehensive but to provide a basis for selecting a smaller number for techno-economic assessment and environmental life cycle assessment. Further background information on the consortium is given in appendix 1.

The main objective of theme 6 is to provide a detailed systems analysis of bioenergy conversion options, incorporating an integrated assessment of technical, economic, social and environmental aspects of UK bioenergy implementation. Part of this work requires an assessment of the available biomass resources (including wastes, residues, crops and imports). Our aim is not to quantify the total available resource, nor to attempt any detailed assessment of how much of this we might use in the UK. Others (mainly within TSEC Biosys) are focusing on the economic, trade and sustainability issues associated with the emergence of biomass as a traded commodity. Instead our focus, in Supergen, is on the entire system – so we must be aware of which feedstocks are likely to be available, their differing profiles, how they can be utilised within the overall system and the social and environmental consequences of doing so, in order that we can provide information that allows end-users to differentiate system (including feedstock) options.

2.1.2 Selection of feedstocks
The choice of feedstocks for this work has been based on a consideration of:

- Which feedstocks are most likely to be material in future UK energy supply
- Inclusion of feedstocks where there is particular consortium expertise or interest
- Inclusion of a sufficiently broad range of feedstocks to allow assessment of heat, power and transport fuel sectors.
- Building upon but not duplicating work already carried out in the first phase of the project (Supergen 1)

A list of the final selected feedstocks is given in table 1.4 and further information on the basis for their selection is given in appendix 2. It should be noted that competing end-uses are considered in relation to the feedstocks not the land, water and other resources that support them. Competition for the latter, and associated prices increases, should be borne in mind.
Table 1.4: Feedstocks chosen for evaluation

<table>
<thead>
<tr>
<th>Feedstock</th>
<th>Significant competing non-energy uses</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Indigenous waste materials/by-products</strong></td>
<td></td>
</tr>
<tr>
<td>Mechanically and biologically treated waste (MBT)</td>
<td>None</td>
</tr>
<tr>
<td>Waste oil</td>
<td>None</td>
</tr>
<tr>
<td>Waste wood</td>
<td>None</td>
</tr>
<tr>
<td>Poultry litter</td>
<td>None</td>
</tr>
<tr>
<td>Straw</td>
<td>Animal bedding/forage</td>
</tr>
<tr>
<td><strong>Indigenous forestry-related materials</strong></td>
<td></td>
</tr>
<tr>
<td>Forestry residues</td>
<td>None</td>
</tr>
<tr>
<td>Forestry-related material (arboricultural arisings and sawmill co-product)</td>
<td>Fibreboard manufacture and similar</td>
</tr>
<tr>
<td>Pellet production</td>
<td>None</td>
</tr>
<tr>
<td><strong>Indigenous energy crops – wood fuel</strong></td>
<td></td>
</tr>
<tr>
<td>Short rotation coppice</td>
<td>None</td>
</tr>
<tr>
<td>Short rotation forestry</td>
<td>Timber</td>
</tr>
<tr>
<td><strong>Indigenous energy crops – grasses</strong></td>
<td></td>
</tr>
<tr>
<td>Miscanthus</td>
<td>Animal bedding</td>
</tr>
<tr>
<td>Switchgrass</td>
<td>None</td>
</tr>
<tr>
<td>Reed canary grass</td>
<td>None</td>
</tr>
<tr>
<td><strong>Indigenous energy crops – other</strong></td>
<td></td>
</tr>
<tr>
<td>Marine biomass</td>
<td>Chemical, pharmaceutical and food industries</td>
</tr>
<tr>
<td>Oil seed rape</td>
<td>Food</td>
</tr>
<tr>
<td>Wheat</td>
<td>Food</td>
</tr>
<tr>
<td><strong>Imported feedstocks</strong></td>
<td></td>
</tr>
<tr>
<td>Jatropha</td>
<td>Oil for illumination &amp; cooking</td>
</tr>
<tr>
<td>Maize</td>
<td>Food</td>
</tr>
<tr>
<td>Palm Oil</td>
<td>Food &amp; oleochemicals</td>
</tr>
<tr>
<td>Palm Kernel Expeller</td>
<td>On site power &amp; animal feed</td>
</tr>
<tr>
<td>Soya</td>
<td>Food &amp; chemicals</td>
</tr>
<tr>
<td>Sugar cane</td>
<td>Food</td>
</tr>
<tr>
<td>Sweet sorghrum</td>
<td>None</td>
</tr>
<tr>
<td>Cynara cardunculus</td>
<td>None</td>
</tr>
<tr>
<td>Olive cake</td>
<td>None</td>
</tr>
<tr>
<td><strong>Traded products</strong></td>
<td></td>
</tr>
<tr>
<td>Ethanol</td>
<td>None</td>
</tr>
</tbody>
</table>

The assessment of each feedstock generally covers the following areas (with some deviations to accommodate the variations between feedstocks)

- Feedstock description
- Feedstock origin
- Environmental and ecological impacts
- Production
- Economics
- Social context
- Constraints

In terms of sources, documents with cogent arguments and data are used from a wide variety of backgrounds: in addition to academic peer-reviewed sources, papers by NGOs and NGO groupings, commercial and research organisations and consultants commissioned by governments are all important sources of information and comment in this field. Webpage material has also been used where the source appears
knowledgeable. Material with an explicit advocacy purpose (commercial or political) is useful for understanding arguments, debates and perceptions and often cites material with less of an advocacy role.
3. Mechanically and Biologically Treated Waste (MBT)

3.1 Feedstock description

Archer at al [2] note that MBT is not a precisely-defined term and that it is best seen as referring to a wide range of technologies. Nevertheless, their approach to MBT technology definition is to restrict the term to deliberately integrated MBT systems, thus excluding, for example, composting systems that have a small element of mechanical treatment at the waste screening stage. Similarly, they restrict their analysis to mixed Municipal Solid Waste (MSW) and exclude green waste and commercial/industrial applications.

This constitutes a typical understanding of MBT, though it can be defined more generally. Lornage et al [3] cite a definition of MBT used by the German Federal Environment Minister [4] as the processing or conversion of waste from human activities with biologically degradable components via a combination of mechanical and other physical processes with biological processes.

Nevertheless, assuming MBT is from MSW, it will at the input stage reflect regional waste characteristics. For example, the French sample used by Lornage et al [3] consisted of 55% (w.b.) of organic waste (incl. 29% (w.b.) of kitchen and green waste, 24% (w.b.) of paper and cardboard), 14% (w.b.) of plastics, 11% (w.b.) of glass, 7% (w.b.) of textile (incl. 4% (w.b.) of sanitary textile), 3% (w.b.) of metals and 10% (w.b.) of other non-biodegradable wastes.

In terms of MBT feedstock properties, it should first be noted that an MBT process will generally have more than one output. Of these, solids and biogas may be useful as a fuel. Solid fuel applications include: co-fuel for direct combustion in power plants, fuel for indirect combustion in power plants, co-fuel for cement kilns, co-fuel for industrial boilers, fuel for dedicated a incinerator or gasifier or co-fuel for an existing incinerator [2]. The biogas may be used to produce electricity, heat or for transport; or it may be blended with landfill gas and/or syngas from waste gasification (ibid). For this reason we here discuss more forms of treated waste than RDF or SRF alone.

The term Solid Recovered Fuel tends to refer to waste made to a defined specification and can be distinguished from lower grade, more variable quality Refuse Derived Fuel (RDF) [2]. A report for DEFRA [5] states that as of 2007, the prevalent term used for a fuel produced from combustible waste is Refuse Derived Fuel (RDF) and that a CEN Technical Committee (TC 343) is currently progressing standardisation work on fuels prepared from wastes, classifying a Solid Recovered Fuel (SRF). Preliminary standards have been published in June 2006. The technical specifications classify the SRF by thermal value, chlorine content and mercury content. A validation project on solid recovered fuels [6] is pursuing a standardisation process [5].

3.2 Feedstock origin

‘Waste’ is legally defined at EC level as ‘any substance or object which the holder discards or intends or is required to discard’ [7]. The UK Biomass Task Force [8] lists those types of biomass-based waste (or residue) which have the potential to provide a reliable source of energy feedstock as including the biodegradable fraction of municipal solid waste (MSW), clean waste wood, animal and food wastes, sewage sludge and refuse derived fuel (RDF) from MSW or commercial/industrial waste.
As a process, MBT is intended to stabilise biodegradable organic matter contained in MSW in order to limit methane emissions and the amount and the pollutant load of landfill leachates, as well as to reduce the volume and mass of waste to be deposited [9-11]. The aerobic pre-treatment of waste also leads to a rapid establishment of methanogenesis once the wastes are landfilled [3, 12, 13]. Although we have stated above that MBT usually deals with household MSW, commercial waste is a possibility and the household waste may be ‘grey bag’ or ‘black bag’. That is, the residual fraction remaining after a kerbside recycling scheme, or fully mixed household waste [2]. In the UK it can be assumed that the predominant feedstock to MBT will be residual waste (ibid: 7.9). Most European MBT suppliers do also assume that a high degree of source separation has taken place (ibid: 7.11), though there are firms beginning to produce MBT systems designed for unsegregated waste.

### 3.3 Production

This section draws particularly on a report [2] intended as an independent assessment of MBT, commissioned from Juniper Consultancy Services for the Sita Environmental Trust, an organisation disbursing landfill tax credits on behalf of the waste management company Sita UK. Archer et al (ibid) review 27 MBT processes from 11 countries and classify these by primary output. Companies producing working machinery with SRF as an output were: EcoDeco, Herhof and Nehlsen (ibid).

There are a wide variety of MBT technologies. In general, Archer et al [2] refer to the mechanical aspect as relating to the “sorting, separation, size reduction and sieving technologies in varying configurations to achieve a mechanical separation of waste fractions into potentially useful products and/or streams suitable for biological processing”; the biological aspect as relating to “an aerobic or anaerobic biological process which converts the biodegradable waste fraction into a compost-like output (CLO) and, in the case of processes incorporating AD (Anaerobic Digestion) biogas” (ibid: 2.7); and the treatment aspect as relating to the integration of process elements (ibid: 2.8). The biological treatment sometimes precedes the mechanical treatment, the most common variant of which is ‘bio-drying’, in which the initial biological process partially dries the waste (ibid: 2.9).

Archer et al (ibid) identify eight generic options or scenarios for MBT process combinations that are broadly representative of the range of possibilities. These are not configurations in the engineering sense but focus on inputs and outputs. One option simply aims to use MBT to pre-treat waste to reduce its volume and its biodegradability, leading to a bio-stabilised residue. Two further options aim to produce a compost-like output, one for use as a compost and one for use as a lower-grade soil improver. A fourth option aims to produce refuse derived fuel (RDF) and a fifth uses the bio-drying variant of MBT to produce a fuel for specific users (solid recovered fuel or SRF). A sixth option is to integrate MBT with a dedicated thermal waste processing unit, to guarantee an outlet for the fuel fraction while reducing the scale of the thermal treatment required. The seventh and eighth MBT options aim to produce biogas via anaerobic digestion, with one assuming that the digestate will be used as a soil improver and the other assuming that it will go to landfill [2]. Of these eight options, option 4 (RDF), 5 (SRF), 6 (recover energy via a feed to dedicated combustion or gasification), 7 and 8 (biogas) are relevant to the present context. Most MBT facilities are currently at a scale of less than 100,000 Tpa, though the largest facility in the world in 2005 was on the outskirts of Madrid at 480,000Tpa (ibid).
Archer et al [2] Figure A1) provide a matrix of typical mechanical and biological process elements used in MBT (Table 3.1 below).

**Table 3.1 typical mechanical and biological process elements used in MBT ([2] Figure A1)**

<table>
<thead>
<tr>
<th>Process Stage</th>
<th>Possible Process Elements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mechanical</td>
<td>Trommel (static or vibrating) Magnet</td>
</tr>
<tr>
<td></td>
<td>Eddy current</td>
</tr>
<tr>
<td></td>
<td>Hand picking</td>
</tr>
<tr>
<td></td>
<td>Air classification</td>
</tr>
<tr>
<td></td>
<td>Near Infrared</td>
</tr>
<tr>
<td>Biological</td>
<td>Open windrow/composting</td>
</tr>
<tr>
<td></td>
<td>In-hall composting</td>
</tr>
<tr>
<td></td>
<td>Tunnel composting</td>
</tr>
<tr>
<td></td>
<td>In-vessel composting</td>
</tr>
<tr>
<td></td>
<td>Anaerobic digestion</td>
</tr>
<tr>
<td></td>
<td>Percolation</td>
</tr>
<tr>
<td></td>
<td>Bioderying</td>
</tr>
</tbody>
</table>

**3.4 Economics**

A key driver of the economics of MBT is the EU Landfill Directive of April 1999 [14], which requires a reduction in the biodegradable fraction of municipal solid waste (MSW) going to landfill, relative to 1995, by 25% by 2006; by 50% by 2009 and by 65% by 2016. However, the potential of MBT as a major source of bioenergy is uncertain [2], despite the significant theoretical potential of residual commercial and household waste as a source of renewable electricity [15]. More specifically, Archer et al [2] section 9.5-7 state:

“Our analysis indicates that the challenges associated with using the output as a compost or a fuel are significant…In the case of fuel applications, the key issue is that the MBT output is simply less attractive to users than other fuels for a mix of technical, economic, legal and regulatory reasons”.

This may seem an odd conclusion, as waste in general and MSW in particular is produced on a substantial scale. Denmark, for example, derives 3.6% of its electricity supply from municipal waste [16], though this is relatively small in terms of the energy system as a whole. DEFRA (ibid) expects 25% of municipal waste to be sent to EfW plants by 2020, compared to 10% today. Moreover, the electrical energy equivalent of one year’s municipal waste in the UK is the same as 5 to 6 million tonnes of coal [17], a value that could be roughly doubled if the heat were recovered (ibid).

However, the energy used to produce and dry MBT, and the inefficiency of its subsequent co-firing, entails a reduction in the efficiency of MBT as an overall process to about 30%, little better than the efficiency of raising steam for electrical generation via direct incineration (ibid). Although MBT renders MSW inert, more easily stored and handled, it is not clear that this will be perceived as compensating for its costs.

Archer et al [2] summarise the fuel-related problems of or obstacles to MBT as:

**Biogas**

- Uncertain regulatory status of the emissions from the gas engines
- Market outlet required for the digestate, or would have to be landfilled
Solid fuel

- Reluctance on the part of the power industry and many industrial facilities to use waste derived fuels
- Concerns about possible corrosion or erosion problems in co-combustion boiler tubes etc
- Potential changes regulatory status of co-combustion facility when burning wastes
- Impact on community relations for the user (‘burning waste’)
- Limited capacity for waste-derived fuels within the cement industry
- Concerns about the long term security of outlets and hence ‘bankability’ of projects
- Insufficient fiscal incentives for waste co-combustion relative to biomass feeds and novel technologies.

Use of the fuel in a dedicated EfW plant

- Likely to be more costly than just incinerating all the waste
- Possible delays in securing planning permission for EfW element may impact on BMW diversion rates.

Archer et al (ibid: 9.48) state: “Although much of the industry has focused on fuel usage over the last two years, we have concluded that, under current market conditions, accepting the output from MBT plants as a fuel is likely to be unattractive to many end users…Our review of the actual usage to which outputs from MBT reference plants are put indicates that relatively few produce a fuel…”.

On the other hand, drivers for MBT will likely strengthen in the UK in future. A consultation on the Renewable Obligation (RO), published alongside the Energy White Paper, set out the proposed levels of support under a banded RO, including greater support for anaerobic digestion, gasification and pyrolysis [16]. In addition, the Government has now removed barriers to the burning of secondary recovered fuel (SRF) alongside ROC eligible biomass at co-firing stations and proposes to facilitate the accreditation of eligible schemes by the regulator (Ofgem) through deeming the energy content of mixed wastes.

The UK Biomass Task Force [8] argued that wastes – both municipal solid wastes (MSW) and animal wastes - offer the greatest immediate sources of bioenergy, with 2.5 million tonnes of MSW already being used for energy generation and a fourfold increase in available tonnage anticipated by 2010. The Task Force noted that the development of Refuse Derived Fuel (RDF) from MSW, although offering improved handling characteristics, higher calorific values and a more consistent burn than MSW, has had restricted market penetration to date due to the need to burn it in Waste Incineration Directive-compliant plants (ibid:2.6).

The Task Force (ibid: 4.21) also referred more generally to the potential for energy generation from waste materials in England as significant. In 2006, only some 2.5 million tonnes (c.9%) of the 29 million tonnes of MSW produced annually in England was used for energy recovery, and energy recovery from waste (EFW) accounted for some 0.7% of the UK’s annual electricity consumption [18]. Even with increasing recycling rates reducing the quantity of available wastes, it is predicted that by 2010 the amount of waste that will need to be incinerated or recovered will reach 10 million
tonnes; current capacity for municipal waste incineration is 2.8 million tonnes per year ([8] ibid).

Archer et al ([2] ibid: 12.2) note that the range of possible costs for an MBT plant will be far wider than for other types of waste processes because of the inherent flexibility of MBT. Even the same facilities using processing plant from the same company at the same capacity can have different capital and operating costs if users have different recycling and refinement (maturation, removal of contaminants) objectives (ibid: 12.3). Archer et al ([2] ibid) caution against the use of headline costs produced by companies, as these are specific to national conditions and particular waste streams. In fact they judge the comparison of such costs to be so misleading that they include them as an annex and not in their main report.

Nonetheless Archer et al ([2] ibid) do make some comments on the costs of MBT relative to other methods of waste management. They state that while the capital costs vary widely, they are generally much lower than for incineration (ibid: 12.10). On the other hand, the operating costs of MBT are normally higher than those for an incinerator, though this is not always so. Critically, the economics of MBT depend upon how the output is used. [2] (ibid: 12.12) found that generation of biogas via MBT is associated with the largest reduction in gate fee (being eligible for ROC payments), while RDF, CLO and stabilised residue to landfill are associated with the highest increase in gate fee. SRF was associated with both a high increase and decrease in gate fee. [2] (ibid) conclude that the overall economics of MBT will be increasingly dominated by the policy context: taxes, incentives, tradeable permits and credits and fines.

Archer et al [19] compare MBT process designs with biogas (two designs) and solid fuel (three designs) as a primary output. In both of the biogas cases, the gas was cleaned and used in an on-site engine to generate electricity for export and sale to the grid, with the gas classed as a renewable fuel. Heat exchange systems recovered the heat generated and used it in the AD process. Regarding MBT systems designed to output a solid fuel, [2] (ibid: Figures A30, A31) provide typical proximate and ultimate analyses for these outputs, using information from multiple sources.

### 3.5 Environmental and ecological impacts

In terms of regulation, [20] state that if an MBT plant processes over 50 tonnes per day it can be assumed that it will require a Pollution Prevention & Control (PPC) permit, while if processing less than this quantity a waste management licence would be required. If the process produces a fuel (e.g. RDF) rather than a waste, then it will be subject to PPC irrespective of the tonnage threshold. The Environmental Permitting Programme (EPP) to be implemented in April 2008 will combine waste licensing and permitting systems. MBT plant are of course subject to land use planning law and an EIA may be required (ibid: 26).

Aerobic digestion processes tend to involve the following emissions to air: CO₂, H₂O, organic contaminants (Total Organic Carbon), NH₃, bio-aerosols (micro-organisms and other very small biological particles, which are typically respirable), fine particulates ([19]: A5.81). In anaerobic digestion, the gaseous contaminants from waste digestion are incorporated in the biogas. Pollutants in the gas engine exhaust include CO and NOₓ but probably not heavy metals, as these are unlikely to be volatilised at the relatively low temperature of AD (ibid: A5.85).
From the mechanical stages of MBT, fugitive emissions to air tend to include: fine particulates (dust), bio-aerosols and odour, usually controlled by channelling the air via negative pressure to a bio-filter [often an extensive thick mat of woody biomass with micro-organisms that can degrade odorous contaminants] or thermal oxidiser) (ibid: A5.89). MBT designs that include a thermal stage produce a different range of gaseous emissions due to the high temperatures involved. Emissions may include acidic gases, heavy metals, VOCs, dioxins/furans and particulates (ibid: A5.92). In the UK, emissions from thermal processes that treat waste or waste-derived materials are controlled under the Waste Incineration Directive (WID), so that MBT processes with integrated thermal treatment will require abatement systems that meet WID (ibid: A5.92). Enviros Consulting [20] also refer to the need to avoid the build up of flies through good management and that odour control may also be achieved through an elevated stack or combustion of the odorous air.

Waste treatment processes also involve emissions to water; indeed, aerobic processes require moisture: below about 40% moisture, composting becomes inhibited and water would usually be added to sustain digestion. Water passing through the waste pile extracts solids (dissolved or suspended) and the result is a leachate (ibid: A5.108). Leachate can also be produced from MBT processes that do not involve the addition of water, including from a bio-drying stage and from a maturation stage in which rain water passes through storage piles. The leachate contains various readily biodegradable (and hence odorous) compounds, nitrates and organic acids that need treating before discharge to sewer (ibid: A5.111).

Anaerobic digestion also produces a digestate and a liquid effluent, the latter being recovered at a dewatering stage and having a relatively high COD (chemical oxygen demand) (ibid). Regarding residues to land, when MBT processes are configured to produce SRF, the solid residue going to landfill can be some 20 wt% of the input mass (ibid: A5.116). If the SRF does not find a market, it too may be landfilled, meaning that 70% of the original input waste would be landfilled (ibid). RDF will generate ash if used in a dedicated on-site boiler, as well as gas cleaning residues following flue gas abatement due to the need to comply with the WID. Both will go to landfill (ibid: A5.118).

Arch er et al [2] also discuss the potential health impacts of MBT. They emphasise that at the time of their writing, no health impact studies directly relating an MBT plant had been carried out, but that there had been work that discussed the risks associated with composting plants. They state that while the MBT process could entail heavy metal contamination and exposure for workers, the neighbouring community or those exposed to its products (similarly for composting and AD of MSW), the health risks can be satisfactorily addressed in a modern and professionally managed facility, providing a detailed assessment of the issues is conducted (ibid: A5.120). They point to a report for DEFRA [5] which found that no studies of the potential health impacts of MBT had been carried out. Archer et al (ibid) judge that it is the bio-aerosols that pose the greatest risk. While this applies most directly to composting plants, it may also apply to workers in MBT plants that include hand-picking lines (ibid: A5.123). A brief look at the more recent literature suggests that the risks posed by bio-aerosols still remain under-researched [21].

3.6 Social context

DEFRA [22](2007: 77) comments that the recovery of energy from waste has been held back by public fears over alleged health effects, and fears that the development
of suitable infrastructure would lock in wastes which could otherwise be minimised or recycled. DEFRA comments that concern over health effects is most frequently cited in connection with incinerators, though it is worth noting that the public tends to view combustion-related bioenergy as similar to incineration (Barker and Riddington, 2003) and have raised concerns about the gaseous emissions from such plants (Upham and Shackley, 2007).

In DEFRA’s view, research shows no credible evidence of adverse health outcomes for those living near incinerators (DEFRA 2007: 78). DEFRA states that the relevant health effects – primarily cancers – have long incubation times, but the available research demonstrates an absence of symptoms relating to exposures twenty or more years ago, when emissions from incineration were much greater than they are now. DEFRA refers to a short position statement on the health impacts for municipal waste incineration, issued by The Health Protection Agency, which reaches similar conclusions. Nonetheless, public concern about incineration, EfW and energy from biomass residues has been experienced in several European countries [23]. Common concerns were identified as:

- Atmospheric Emissions: dioxins, acid gases, heavy metals
- Disposal of fly ash from incineration or residues from energy from biomass residue plant
- Noise, odour, traffic movements
- For EfW: lack of flexibility of contracts for municipal solid waste and their impact on new reduction or recycling initiatives and importation of waste from outside the region
- Insufficient justification of the plant (the principle, size or scale)
- Costs and security of finance
- The visual impact of the scheme on the locality
- The impact of the scheme on the character of an area
- The impact of the scheme on local house prices (ibid: 66).

DEFRA [16] argues that evidence from neighbouring countries, where very high rates of recycling and energy from waste are able to coexist, demonstrates that a vigorous energy from waste policy is compatible with high recycling rates (see their chart 5.2). In the UK Government’s view, the key to ensuring that both are achieved is, firstly, excellent quality consultation between stakeholders, at an early stage when local waste strategies are being developed; and, secondly, planning and building facilities with an appropriate amount of flexibility built in. This means flexible, for example, modular – buildings, and also flexible contracts, so that local authorities are not locked in to treating fixed quantities of waste.

Enviros Consulting [20], for DEFRA, discuss the social and perception issues associated with MBT. They comment that while many people are now supportive of the need for waste reduction, recycling and to a lesser extent the need for new waste facilities, new waste facilities of whatever type are rarely welcomed by residents close to where the facility is to be located (ibid: 28). More generally, there is a relatively low level of public understanding of the concept of MBT by the public, with the technology scoring inconsistently when explained in detail as a residual waste treatment technology (ibid: 29).
3.7 Applications
Enviros Consulting [20], in a report for DEFRA, summarise the markets and UK plants using RDF. At the time of writing there is only one dedicated conventional combustion plant (incinerator) in the UK that uses RDF as a fuel to generate electricity. This is operated by Slough Heat and Power and takes 100kt/yr. Another facility that accepts prepared fuel, generated from raw MSW and which could be termed crude RDF, is a fluidised-bed incinerator in Kent, operated by Kent Enviropower and taking 500kt/yr.

RDF may also be utilised within some Advanced Thermal Treatment (ATT) processes and the co-combustion market and it is currently anticipated that cement kilns, along with large industrial energy users and the power generation sector, will provide the majority of potential capacity for using RDF ([20], ibid). There is however, competition from other wastes that can be processed within the cement production process including tyres, some hazardous wastes, secondary liquid fuels etc. Consequently it is expected that there may be competition (and competitive gate fees) for acceptance of RDF at cement kilns (ibid: 15).

As stated, electricity generated from the biodegradable fraction of waste is eligible for support under the Renewables Obligation (RO). While WID compliance could represent a significant capital investment for the power industry, use of a single boiler for this purpose would reduce the cost (ibid). Electricity generated from the biomass component of RDF also qualifies for support if it is generated in ‘advanced conversion technologies’, including pyrolysis or gasification plants (ibid).

Enviros Consulting [20] for DEFRA state the predicted market size for RDF in the UK as:

- 350,000 t/a in cement kilns [24]
- 300,000 – 600,000 t/a in the paper industry (this would require construction of dedicated RDF plant at paper mills) [24]
- also 500,000 t/a packaging and packaging waste, including municipal derived RDF, in UK Cement Kilns [British Cement Association in [20]]

3.8 Constraints
MBT has modest potential as a processed fuel source, constrained by the volume of transportable waste. MBT plants operate in markets that are necessarily bounded by significant regulatory complexity and hence cost, plus limited markets for secondary materials. Supported by recycling and energy recovery policies, MBT may fulfil its potential as a relatively centralised means of waste processing and fuel recovery. Much depends on local authority and public opinion, particularly the level of opposition to EfW incineration.

3.9 Conclusions
The prospects for MBT are uncertain. Currently, it appears that MBT has a small though useful role to play in the UK, in terms of supplying a bioenergy feedstock. Its RDF output is most likely to be used as a fuel for cement kilns, paper processing and co-firing for electrical power. Although RDF is based on a waste, treatment via MBT involves efficiency and financial penalties that are not incurred by incineration (dedicated EfW plant). On the other hand, MBT plant are substantially less expensive to construct. Thus while residual-based EfW has a substantial role to play as a form of
bioenergy - theoretically, up to 17% of UK electrical supply [15], the role of MBT specifically, relative to EfW incineration, and relative to other forms of waste treatment with a heat, electrical or fuel output, is unclear.
4. Waste vegetable oil

4.1 Feedstock description

Cooking oil is produced from vegetable and nut sources with a high fat content. The term ‘used cooking oils’ refers to cooking oil which has been used in food production and which is no longer viable for its intended use [1]. Used cooking oil arises from many different sources, including domestic, commercial and industrial. DEFRA [25] estimate that 75,000 tonnes of waste vegetable oil arise from catering and industrial sources annually in the UK. Nonetheless, it is difficult to estimate this quantity due to the lack of an established collection infrastructure for domestic consumers: most cooking oil wastes are disposed of through normal mixed waste disposal methods or flushed into the sewerage system [1].

WasteWise [26] summarise the properties and production of biodiesel from used cooking oil. Vegetable oils are triglycerides, i.e. compounds formed from fatty acids and glycerol. Three fatty acid molecules link with each glycerol molecule and the link is a bond between two oxygen atoms, known as an ester link. Vegetable oils are tri-esters. Glycerol (also known as glycerin) is a type of alcohol that can function as a skin emolient and hence is useful additive for the cosmetics industry. The triglyceride molecules are large compared to those in petrodiesel – each fatty acid comprises a chain consisting of around 18 carbon atoms in the case of rapeseed oil, for example, making 54 carbons in addition to the 3 in the glycerol. Petrodiesel, in contrast, contains carbon chains averaging around 12-14 atoms in length. This difference in molecular size is one of the main reasons for the unsuitably high viscosity of vegetable oil for use as a fuel. During bio-diesel manufacture, the oil is split into smaller carbon chains by a process known as transesterification [26].

SEPA [1] describes the two methods by which used cooking oils can be recovered for use as biodiesel. The first method involves filtering the used cooking oil for use in a dual fuel engine. The dual fuel engine is started using standard diesel and once hot, the engine fuel supply is switched to biodiesel. The second method is to filter the used cooking oil and put it through an esterification process that produces biodiesel and glycerine as a by-product. This second form can be used directly in diesel engines. Biodiesel can be used in modern vehicles, without modification, providing the fuel meets the EU specification, BS EN 14214.

4.2 Production

In 2000 the total UK production of cooking oils was 2,253,326 tonnes including imports but excluding production for export and resources held in stock (EUROSTAT in [1]). Of this total, 1,461,409 tonnes were for human consumption in household, industrial food processing and catering sources (ibid). Around 80,000 tonnes per annum of used cooking oils arise from catering and industrial sources annually in the UK ([26] in [1], ibid). SEPA [1] state that approximately 65,000 tonnes of the 80,000 tonnes of used cooking oil collected in the UK from commercial and industrial sources originates from commercial catering establishments (81%), with the remaining 15,000 tonnes (19%) arising from the food processing industry.
Until 1 October 2004, companies employed in the collection of used cooking oil from commercial and industrial sources, have sold the used cooking oil for use in animal feed. However, the introduction of the Animal By-Products Regulations 2003 imposed a ban on the use of used cooking oil derived from catering sources being used in animal feed (used cooking oils from manufacturing premises and fresh or unused cooking oil, can continue to be used in animal feed) ([1], ibid, see Box 1 below). The disposal of used cooking oil can be problematic when disposed, incorrectly, down kitchen sinks, where it can cause blockages of sewer pipes when the oil solidifies. Used cooking oil present in high volumes should be collected and disposed of by a dedicated company. When the used cooking oil is present in insufficient quantities for collection and decanting, it should be mixed in with the municipal waste. Used cooking oil is thus a potentially problematic waste stream, currently serviced through the ACORN (Affiliated Cooking Oil Reclaimers Nationwide) a collection infrastructure, and companies offering a free collection service as a result of its value as a biodiesel feedstock are thus likely to be welcomed by caterers.

**Box 1 Legislation affecting the way that used cooking oils can be managed (SEPA, 2005)**

| The Animal By-Products Regulations 2003 | that came into force on 1 October 2003 implement the EU Animal By-Products Regulations (1774/2002) that have applied to member states since 1 May 2003. The Regulations lay down strict animal and public health rules for the collection, transport, storage, handling, processing and use or disposal of all animal by-products. The Regulations place a ban on the use of catering waste if it is destined for animal nutrition. |
| Catering waste is considered waste from premises on which food is produced for direct consumption and includes used cooking oils originating from such establishments. The majority of used cooking oils collected for recovery in the UK has historically been supplied to the animal feed industry. The EU granted the UK’s request for transitional measures in respect of the ban on the feeding of used cooking oils to animals which came into force on 1 October 2004 (SEPA, 2005). |

WasteWise [26] summarise the production of biodiesel from used cooking oil as follows.

(i) **Filtering, neutralisation and drying**

The waste vegetable oil needs to be filtered to remove any food particles that may clog up fuel lines. Free fatty acids, which are present in higher concentration in used oil than fresh, then need to be neutralised with alkali. Finally, the oil must be dried, as water reduces the efficiency of the transesterification.

(ii) **Transesterification**

The oil is typically reacted with about a fifth by volume of methanol and a small amount of sodium hydroxide (caustic soda). This results in a break-up of the triglyceride molecules and formation of the fatty acid methyl esters (FAME) which
comprise bio-diesel. Thus bio-diesel made from primarily rapeseed oil is known as rapeseed methyl ester, for example. Glycerol is also formed as a useful by-product [26].

WasteWise [26] state that ethanol can be used as a less toxic alternative to methanol, to form fatty acid ethyl esters (FAEE). This process is popular in the US as ethanol can be formed from biomass, whereas methanol is still largely produced from oil, although alternative production methods from biomass and natural gas do exist. Performance and emission characteristics of FAME and FAEE bio-diesel appear similar so in the longer term it would be preferable to manufacture FAEE fuel. Current barriers include the need for extremely dry ethanol for the reaction to occur cleanly. Transesterification is considered in more detail below.

(iii) Washing and drying
The bio-diesel then needs to be washed to remove the residual methanol (about a tenth by volume) and soapy deposits. The glycerol settles out as a separate layer in a procedure facilitated by using a sand bed. It should be possible to sell the glycerol to soap and cosmetics manufacturers for purification to pharmaceutical grade glycerol. Alternatively, it may be possible to use it within local soap-making enterprise. The glycerin at this stage is coloured as it contains dyes from the waste oil – this is removed by filtration through charcoal. Finally the bio-diesel is dried by heating or passing through a salt bed.

(iv) Equipment
WasteWise [26] state that equipment for small-scale, automated bio-diesel production can be obtained fairly cheaply. For example, Savoia Power in Argentina make a unit for ca. £2,400 (the BIO 4) which produces 400 litre batches. A smaller, 200 litre unit (the BIO 2) is also available for £1,400. They also make an accessory for filtering and vacuum drying waste oil prior to conversion (the BIO-D2. This has a throughput of 200 litres per hour and costs £1,600.

Transesterification methods
Zhang et al [27] provide four different continuous process flowsheets for biodiesel production from virgin vegetable oil or waste cooking oil under alkaline or acidic conditions on a commercial scale. Kulkarni and Dalai [28] detail five methods for the transesterification of waste cooking oil. These are summarised below. The methods entail using alkaline, acidic, or enzymatic catalysts. Depending on the undesirable compounds (especially free fatty acids [FFA] and water), each catalyst has its own advantages and disadvantages (ibid):

- **Alkali-Catalyzed Transesterification** - common alkaline catalysts (such as NaOH, KOH, and NaOCH3) are used. The rate of alkaline-catalyzed transesterification reaction is fast, compared to that of using acids, but is somewhat limited because the FFA in waste cooking oil reacts with the alkaline catalyst and forms soap, which prevents glycerol separation, and so drastically reduces the ester yield. The water in waste cooking oil also affects the methyl ester yield by favoring a saponification reaction [28].

- **Acid-Catalyzed Transesterification** – the advantage of this option relative to alkali catalysis is that an acid catalyst (e.g. HCl and H2SO4) is insensitive to FFA; however, it has a slower reaction rate, though this can be reduced by the use of excess alcohol. Currently, a focus of biodiesel research is on the use of a solid acid catalyst for the transesterification of the low-grade oils that have a high FFA content [28].
• **Acid- and Alkali-Catalyzed Two-Step Transesterification** - An acidic catalyst can be used initially to convert FFA to the esters and to decrease the FFA level to <1%. In the second stage, the transesterification of oil can be performed using an alkaline catalyst. The approach can increase yield and reaction rate, plus reduce unwanted by-products and FFA. However, it requires either the removal of the acid catalysts or the addition of additional alkali, both of which increase costs [28].

• **Enzyme-Catalyzed Transesterification** - chemical (acid or alkali)-catalyzed transesterification of waste cooking oil has problems, such as pretreatment of feedstock, recovery of glycerol, removal of the catalyst, and the energy-intensive nature of the process (high stirring speed, and temperature required for good conversions). Enzyme (such as lipase)-catalyzed reactions have advantages over traditional chemical-catalyzed reactions: the generation of no byproducts, easy product recovery, mild reaction conditions, and catalyst recycling. Also, enzymatic reactions are insensitive to FFA and water content in waste cooking oil. The enzymatic alcoholysis of pure triglycerides with or without solvent has been well-documented [28].

• **Catalyst-Free Technology for Transesterification** - novel methanolysis processes are being developed for the synthesis of biodiesel from vegetable oils using noncatalytic methods. The disadvantages that result from the use of a catalyst and its removal from the products are eliminated with noncatalytic transesterification reaction of vegetable oils with alcohol. The use of supercritical methanol for the production of biodiesel is one such emerging technology [28].

### 4.3 Economics

SEPA [1] judge that the potentially high commercial value of used cooking oil as a waste resource, averaging £160 per tonne (May 2005) and the emergence of the biodiesel end market, means that it is likely that the established ACORN collection infrastructure for commercial and industrial sources of used cooking oil will remain.

Argent Energy (UK) Limited operates the UK’s first large-scale biodiesel plant. The plant, which is near Motherwell in Scotland, started production of biodiesel in March 2005. Argent makes biodiesel from tallow and used cooking oil - by-products of other industries which have few alternative uses. However, the plant is also capable of using a wide variety of raw materials including virgin oils such as rapeseed oil. The biodiesel is produced to EN 14214 2003 (the European Standard for biodiesel as an automotive fuel for diesel engines). Planning permission has been granted for a second plant at Ellesmere Port in Cheshire. The proposed second plant is planned to have an annual production of 170 million litres - more than three times the capacity of the existing plant. Phase 1 of this will provide 85 million litres of production capacity and the infrastructure to double that as the market develops [29].

Argent [29] describes as critical to the economics of its operation the fact that since July 2002 the UK duty on biodiesel has been 20 pence per litre lower than the duty on fossil road fuel. The 2007 UK Budget indicated that this incentive would remain until 2009-10 and that after this, a buy out price -the price paid by fuel suppliers who failed to meet their obligation - will be introduced at 15 pence per litre. The 2007 budget also announced that the RTFO would rise above 5 per cent after 2010-11, provided three factors are met: there need to be robust sustainability and carbon emissions...
standards; there need to be new fuel quality standards at EU level to ensure that existing and new vehicles can run on biofuel blends higher than 5 per cent; and that the costs need to be acceptable to the consumer and wider economy.

Zhang et al [30] state that the use of waste cooking oil should greatly reduce the cost of biodiesel because waste oil is available at a relatively low price. They report that as of 2002, virgin feedstock costs approximately one and a half times that of petroleum-based diesel depending on feedstock oils. They also report that approximately 70–95% of the total biodiesel production cost arises from the cost of raw material; that is, vegetable oil or animal fats ([31]; [32], in [33] ibid). Kulkarni and Dalai [28] provide more recent confirmation that a major hurdle in the commercialization of biodiesel from virgin oil, in comparison to petroleum-based diesel fuel, is its cost of manufacturing, primarily the raw material cost.

4.4 Environmental and ecological impacts

The environmental implications of using waste cooking oil as a fuel are, in themselves, positive. The assessment by Zah et al [33] (see the chapter on corn/maize) shows recycled vegetable oil to be one of the best-performing of all the biofuel feedstocks that they assess, both in terms of net GHG emissions and in terms of wider environmental impact. Zah et al [33](ibid) estimate the GHG reduction of recycled oil as some 70-75% relative to low sulphur petrol, and total environmental impact as some 50% relative to low sulphur petrol, as indicated with the LCA eco-indicator 99 method. However, it should be remembered that this positive impact arises from substitution not from production per se: intensive agriculture, from which the vegetable oil arises, is not an environmentally benign activity. If use of recycled vegetable oil drives an increase in the production of the virgin feedstock, absolute impact will rise, but at a slower rate relative to a scenario in which the waste oil is not made use of.

4.5 Social context

Biodiesel made from waste/used vegetable oil is likely to be generally received positively in most quarters, with the proviso that its limited supply potential will also be apparent to most. Collection offers the potential to engage citizens/consumers positively in environmental mitigation aspects of transport and thus has some degree of educational potential. There may still be local objections to refinery infrastructure, depending on local contingencies (such as the proximity of residential accommodation to plant and vehicles).

An example of the public engagement opportunities offered by waste vegetable oil is the launch by Stagecoach (26 October 2007) of an initiative allowing customers to exchange used cooking oil for discounted bus travel [34]. The press release stated that eight vehicles in Kilmarnock would run on 100% biodiesel manufactured from used cooking oil and other food industry by-products, resulting in an expected 82% reduction in CO₂ emissions. All households on the Service 1 route, which runs from Stewarton to Darvel via Kilmarnock and carries around 15,500 passengers a week, received a free container to recycle their used cooking oil. This can then be taken to East Ayrshire Council’s recycling plant at Western Road, entitling customers to a voucher for discounted bus travel [34], ibid.

The press release states that single-deck Bio-buses, running under the slogan “Do your part, be Bio smart!”, have been fitted with bespoke dual fuel tanks as part of the
A project undertaken with Motherwell biodiesel business Argent Energy Ltd. Argent Energy, which operates the UK’s first large-scale biodiesel plant, will provide bulk fuel storage at Stagecoach’s Kilmarnock depot for the duration of the six-month trial and will supply all the biodiesel (ibid).

4.6 Applications
Biodiesel produced from waste cooking oil can be used in diesel generators or internal combustion engines. Waste cooking oil can be used in combustion/other forms of electrical generation/steam-raising activity but flue stacks need to be WID compliant, contributing to this being an unlikely application.

4.7 Constraints
Of all of the feedstocks considered, this is perhaps the most straightforward in terms of defining constraints. DEFRA [25] estimate that 75,000 tonnes of waste vegetable oil arise from catering and industrial sources annually in the UK. Unless this can be supplemented by domestic and/or imported waste oil, then the constraint lies at this level, assuming complete collection. Collecting all of the UK’s used cooking oil could provide 1,460,000 tpa biodiesel, equivalent to 1,622,222,222 litres, exceeding the total requirement estimated for biodiesel under the RTFO.

4.8 Conclusion
Some 75,000t of waste vegetable oil arise from catering and industrial sources annually in the UK. In contrast, DUKES [35] states that 20,146kt of DERV were delivered in the UK in 2006. Of this, 11,453kt were deliveries to retail outlets. As 1kg oil reacts with 0.1kg of methanol to give 1kg biodiesel plus 0.1kg glycerol, commercially-arising waste vegetable oil could only supply a small fraction of potential UK biodiesel demand (0.6% of retail diesel supply). Nevertheless, waste vegetable oil is one of the most environmentally preferable biofuel feedstocks, with the potential for social engagement and education, with a variety of esterification routes.
5. Waste/recovered wood

5.1 Feedstock description
Within this report we aim to cover all wood-based material that would normally be disposed of within the municipal waste stream. This would therefore include demolition wood, wood recovered from building sites, wood disposed of at civic amenity sites and other sources of wood that arises from normal domestic and commercial activities. We do not include within the scope of this forestry and arboricultural material, which is dealt with separately within the resource assessment. We are also not specifically including large-scale industrial arisings of particular wood, timber and related materials. These are often quite specific resources for which there are likely to be particular bioenergy opportunities, which are too varied to be covered in this generic report. Instead we focus here on the more generic forms of packaging and other used wood which tend to arise within the municipal waste stream. Some of this material will be essentially virgin wood, but most will be treated and/or contaminated in some way.

5.2 Feedstock origin
With increasing emphasis within the waste management industry on recovery waste wood is now routinely separated from the main municipal waste stream either at source or by post-collection processes. [36] The biomass task force [8] reported in 2005 that 5-6 million tonnes of wood waste was typically generated each year; of which around 1.4 million tonnes were recovered in 2004. Not all of this is physically recoverable and the task force suggested that an additional 1.5 Mtpa high quality waste wood and 2-3 Mtpa contaminated waste wood could potentially be recovered. In line with recommendations made by the task force the government has set up a strategic group within the Waste Implementation Programme to take forward the national development of wood waste as an energy source. [37]

Government estimates as part of their waste strategy development indicate that recovering energy from a third of the UK’s wood waste which is currently landfilled could generate 2600 GWh electricity and save 1.15 MtCO2 equivalent. [16] It is noted within the waste strategy that wood has a relatively low embodied energy used in production, but high calorific value. This means that, while it may be appropriate to recycle or recover some specific waste streams, use as a fuel generally confers a greater greenhouse benefit than recovering the material as a resource. [38]

The UK produced 11.1 million m3 timber in 2004, a figure forecast to grow to 16 million m3 by 2020. Despite this over two thirds of our wood is actually imported each year: mostly softwood from Scandanavian and Baltic states. [39] In general these softwoods are used in the construction industry (70% of softwood use in the UK), with hardwoods tending to be used for furniture and interior design. Imported tropical wood tends to be used for marine construction and high value interiors. [39] Wood waste generated by householders comes mainly from old furniture, fencing and DIY off-cuts.
5.3 Economics
A study commissioned by Defra in 2002 examined the state of the markets for waste wood in the UK. It found that waste wood formed around 1.2% of collected household waste, amounting to only around 250,000 tpa. However, civic amenity sites in England, Scotland and Wales collected 6.6 Mtpa, growing at a rate of on average around 6% pa. The cost of segregating and processing this material was found to be £20-47/tonne. [40]

5.4 Environmental and ecological impacts
A report commissioned by Defra in 2006 concluded that there were 7.5 Mtpa waste wood arising in the UK and that greenhouse gas savings were greater for thermal treatment of this material via energy recovery, as opposed to recycling/recovery of the material resource, which actually had a net greenhouse gas impact compared to current baseline. [38]

A new UK waste strategy was published in 2007. [16] This retains the traditional waste hierarchy for treatment/disposal of waste materials of reuse and recycling above energy recovery. However it also recognizes that this may not be uniformly applicable to all waste streams and recognizes the findings of the ERM report [38] with respect to greenhouse gas balances for waste wood. It also identifies particular waste stream/action combinations which would have maximum environmental benefits. One of these is developing the energy recovery market for wood waste. A task has been set up related to this which is due to report in April 2008.

The landfill directive restricts the amount of biodegradable waste being sent to landfill in the UK. Timber is not directly targeted in the directive, but is effectively included as a biodegradable constituent of household waste. [39]

The packaging directive affects companies with a turnover of more than £2 million who process more than 5 tonnes of packaging a year and restricts the disposal of timber used in packaging unless recovered or sent for energy recovery.

The waste incineration directive covers the thermal treatment of wastes and specifies certain regulations, emissions and reporting requirements which are generally more onerous than for “clean” fuels. These result in additional costs to the owner/operator of the facility and tend to lead to longer project development times and sometimes more difficulties in obtaining relevant permits/approvals. Thermal treatment of virgin timber is excluded from WID, but will still require a PPC permit from the Environment Agency unless in very small appliances, in which case a waste management licence will suffice. Once used the timber becomes non-virgin and is then not completely excluded from WID. The Environment Agency is the regulatory body and its position is that WID will apply to use of such waste wood unless an operator can demonstrate that the material has not been contaminated by halogenated organic compounds or heavy metals (resulting from treatment from wood preservatives or coatings). [41]

Thermal conversion of waste wood results in a range of airborne emissions to atmosphere. These generally include CO, NOx, particulates and volatile organic compounds. Depending on the exact composition of the wood there may also be releases of SO2, alkali metals and other substances. The emissions profile depends on the feedstock composition, conversion technology and abatement measures implemented. In general wood that has been treated (e.g. by preservatives, paint,
varnish etc.) has potential for greater environmental impacts. Heavy metals, such as copper, chromium and lead are widely present in preservatives and may end up in fly ash and bottom ash when treated wood is combusted. Halogens and halides are of particular concern, as they can form halogenated organic compounds, including dioxins and furans. These are highly toxic organic compounds, with long residence times. If wood contains more than 1% halogenated organic compounds it is classified as hazardous waste and an additional set of environmental regulations apply. [42]

5.5 Social context
There has been limited experience of wood waste implementation in the UK to date and so the related social issues and responses have been largely unexplored. Social issues related to development of bioenergy from wood waste are likely to revolve around the same issues as for other waste materials (see section on MBT waste material). However, utilisation of wood waste material that has previously been treated is likely to give particular concern in relation to potential for formation of dioxins and other organic pollutants.

5.6 Prospects and Status
At present the market for energy recovery from waste wood in the UK is very underdeveloped. There is a substantial resource available which could be diverted from the main waste stream relatively easily, as most of it is currently processed via civic amenity sites. However, the costs of doing this are relatively high and this would have to be passed on to the user. Conversely there is a lack of established end-markets at present. Partly this is due to classification of waste wood as waste under the Waste Incineration Directive, so that in many cases only a limited number of facilities are licensed to accept waste wood material, even when it is of relatively benign origin. At the time of writing there is only one dedicated conventional combustion plant (incinerator) in the UK that uses RDF as a fuel to generate electricity. This is operated by Slough Heat and Power and takes 100kt/yr. One of the actions arising within the UK waste strategy is to develop the market for waste wood for energy recovery, which is to be pursued by the Waste Infrastructure Development Programme. This group is responsible for producing a comprehensive strategy for the construction of the infrastructure necessary to support the waste management strategy.
6. Poultry Litter

6.1 Feedstock description
Poultry litter comprises animal bedding material and manure produced during chicken production. The composition of this natural resource is intrinsically variable. In particular the moisture content of the feedstock varies depending on the birds, their housing conditions, diet etc. One of the most comprehensive studies carried out of UK-originated material was in 1996 but there have been few changes in animal husbandry since then that would invalidate this analysis. [43] It found broiler and turkey litters to have around 60% dry matter content; while layer manures were much wetter at only 35% dry matter content. For this reason most focus for bioenergy is on the broiler litters. However, all litters had similar nutrient ratios. Table 6.1 is taken from the results presented in that study. It represents averaged figures for more than 120 samples (21 for broiler litters alone).

<table>
<thead>
<tr>
<th></th>
<th>% dry weight</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>N</td>
</tr>
<tr>
<td>Laying – battery deep pit</td>
<td>6.0</td>
</tr>
<tr>
<td>Laying – deep litter</td>
<td>2.4</td>
</tr>
<tr>
<td>Laying – slurry</td>
<td>5.6</td>
</tr>
<tr>
<td>Broiler litter</td>
<td>3.4</td>
</tr>
</tbody>
</table>

6.2 Feedstock origin
Chickens are typically housed during production in purpose-built shed-like structures which are fitted out to provide perches, water, food etc. The floors of the chicken houses are generally covered with an absorbent material at the start of a breeding session, which becomes covered in poultry manure and excrement as the birds grow. At the end of a breeding period (typically 8 weeks or so) the chicken houses are cleared out and the bedding material removed and replaced with fresh bedding. A variety of material may be used for bedding, depending on local availability and costs, but this typically includes wood shavings, straw and shredded paper.

Both free-range and more intensive poultry farming methods require to provide shelter for the animals and therefore make use of bedding material, which subsequently becomes contaminated to become poultry litter.

6.3 Economics
Poultry litter is a waste generated by the poultry industry and therefore must be disposed of in accordance with appropriate waste management legislation. In some cases the poultry manure may be spread on farmland. This returns valuable nutrients to the soil, but there is increasing concern about the environmental impacts of this, particularly with respect to emissions of greenhouse gases, such as nitrogen oxides as the poultry litter is rich in nitrogen (including in the form of ammonia) and this contributes to acidification and potentially leaching.

At present there are no direct restrictions on land-spreading of poultry litter, which can offset the costs of using fertilisers to provide soil nutrients and so actually can be considered to have some value. Consequently poultry farmers do not usually pay for disposal of this waste material. The only constraint is that the quantity of poultry
litter than can be landspread is restricted by constraints on soil nitrate levels. ADAS for Defra [44] calculated that this resulted in poultry litter being spread across 200,000 hectares of land in the UK at present. Obviously not all of this land can be accommodated adjacent to poultry production plants and therefore some travel is essential, incurring costs. Poultry producers are therefore generally unwilling to pay for disposal (they can dispose of the material to land for free) but may incur travel costs in their disposal operations. The result is that in the areas of the country identified as having particularly intensive operations it would be possible to site a biomass energy facility which could attract poultry litter by paying a nominal gate fee (effectively to cover transport costs to bring the material to the disposal site). This could be of the order of £10/t. [45]

A report by the Poultry Industry Council stated that existing land-spreading disposal routes cost between £2-10/t to cover transportation and spreading costs.

6.4 Environmental and ecological impacts

Incineration of poultry litter produces a by-product ash material. This contains much of the valuable P and K content that was present in the original poultry litter material in a more pleasant form. The specification of the ash material is typically 18-22% P2O5 and 12-15% K2O. Lime is also present in substantial quantities, both form the original litter and as a result of additions made to control acid gas emissions during combustion. [46] This is recommended as a fertiliser product for use on arable and grassland, provided stock are excluded for a minimum of 2 weeks following application.

Raw poultry litter has traditionally been spread on land as a means of both disposal and of returning valuable nutrients to the soil. The EU animal by-products regulation (EC/1774/2002) has applied to member states since May 2003 and includes untreated poultry litter within its scope, classified as category 2 material. Most category 2 material should be rendered or incinerated. However, litter and manure (along with a small group of other animal by-products) can still be applied to land “if the competent authority does not consider them to present a risk of spreading any serious transmissible disease”

In practice the government has indicated that for England litter and manure may be land-spread unless specific restrictions are applied, which would be imposed, for example, in the case of outbreak of a serious notifiable disease. [25] In particular there have been links between manure spreading and cases of cattle botulism, so that deep ploughing or burial has been recommended by Defra in preference to land-spread. [25]

A review carried out by ADAS on behalf of Defra in 2008 considered the environmental impacts of livestock farming in the UK and found that management of poultry litter was a particular issue because of the high nitrogen content, with its propensity to leaching following application to land. Also ammonia loss from poultry litter and redeposition can lead to acidification and nutrient enrichment of sensitive habitats, leading to losses in biodiversity. [44] Recommendations for addressing environmental issues related to poultry production include: limiting amounts and timing of land-spread, using wood shavings rather than straw as bedding, keeping litter dry, possibly even by in-house fan drying. [44]
Zinc inputs from land—spreading of poultry litter are higher than for any other livestock manure. [44]

6.5 Social context
A report was published by Defra in early 2008, which reviewed the environmental impacts of livestock farming in the UK. [44] The key issues this report identified for the intensive farming sectors (including poultry) were loss of nutrients, sediment and microbial pathogens to water, gaseous emissions to air, soil compaction and contamination. Most of these are associated with manure production, storage and handling.

6.6 Prospects and Status
There is significant variation in estimates of poultry litter arisings in the UK. Existing disposal in the UK focuses on land-spreading with some being incinerated in one of the 4 dedicated poultry litter power stations. Alternatives include composting and anaerobic digestion. [47]

The Poultry Industry Council states that there are 1.4 million tonnes of poultry litter produced annually in the UK; the main disposal route for which is land-spreading as a fertiliser.[48]

A review carried out by ADAS for Defra in 2008 included statistics that showed a steady decline in UK livestock populations from 2000 to 2006, with the exception of poultry, for which laying birds were roughly constants and an increase observed in slaughtering fowl. [44]

According to ADAS/Defra, the annual total arisings from the UK’s 19 million birds are around 4 million tonnes of poultry litter pa. [44] The ADAS review quoted figures from the British Poultry Council that 670,000 tonnes of poultry litter are incinerated annually in power stations, equating to around 75% of chicken litter arising; although ADAS felt this figure was too high.

The Biomass Energy Centre estimates a potential annual supply of around 3.5 million tonnes [49] of poultry droppings (60% dry matter[43],[50]).

There are 4 existing plants in the UK, designed to take chicken litter, with a total declared net capacity of 74.7 MWe. Some of these plants now take other waste fuel such as MBM.

In 1996 the Environment agency estimated annual arisings of 1 Modtpa. [51]

Overall there appears to be wide variation on levels of poultry litter arisings. This could be due to a number of reasons: allowance for the capacity factor of poultry houses (birds are typically breed for a 12 week period, before clearing out for the next flock, so occupancy is not constant and per annum figures for breeders do not make sense as lifespan is much less than this), allowance for moisture content (30-70%), distinction between quantities of poultry excrement and the actual litter mass (including bedding material) and distinctions between the total quantity of material produced and the quantity that is actually tracked through disposal centres as a waste material. Central estimates are of 1-4 Mtpa. Of this less than 1 Mtpa is currently incinerated; leaving a likely resource of 300,000 tpa to 3.3 Mtpa.

It should be noted that for thermal conversion purposes litter from barn-reared chickens is more suitable, as by scratching the litter the birds partially dry it. Litter
from battery chickens are less usable. [45] Of more significance is the fact that this resource is quite widely dispersed and so central collation for incineration probably only makes sense at a few strategic locations in the UK and these are generally where the existing poultry litter plants are sited. Defra collate data, as part of their veterinary surveillance strategy on UK livestock, including poultry. This showed that in 2008 there were a total of 24,269 registered premises, which kept 251,913,661 poultry. The distribution of these premises is significant as it makes sense to treat or dispose of poultry litter as close as possible to the originating point. Key strategic areas where the density exceeds 8000 birds per square kilometre are Suffolk, Powys and north Lincolnshire. There are also high densities in Yorkshire (particularly east Yorkshire) and Devon. [52] There is possibly the prospect of further plants in Yorkshire or Powys. If the plants were sized similar to the existing ones they would each take 100,000 – 500,000 tpa litter, producing a total electrical capacity of 20-75 MWe.
7. Straw

7.1 Feedstock description
Straw is generally traded in baled form, following on-farm production, harvest and processing of cereal crop. Bales are generally produced to standard sizes, as outlined in table 7.1.

Table 7.1: Straw bale dimensions and weights

<table>
<thead>
<tr>
<th>Dimensions (m)</th>
<th>Average weight (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small square</td>
<td></td>
</tr>
<tr>
<td>0.36 x 0.4 x 0.8</td>
<td>13</td>
</tr>
<tr>
<td>0.4 x 0.46 x 0.9</td>
<td>19</td>
</tr>
<tr>
<td>Large round</td>
<td></td>
</tr>
<tr>
<td>1.2 x 1.2 (diameter)</td>
<td>115</td>
</tr>
<tr>
<td>Rectangular</td>
<td></td>
</tr>
<tr>
<td>0.8 x 0.9 x 2.0</td>
<td>215</td>
</tr>
<tr>
<td>1.2 x 1.3 x 2.75 (Hesston)</td>
<td>650</td>
</tr>
</tbody>
</table>

Straw is a natural occurring agricultural residue and, as such, its physical and chemical composition varies widely, particularly with variations in application of agrochemicals during crop growth. Table 7.2 gives some indication of typical properties, based on analyses of reference materials undertaken within phase 1 of the Supergen bioenergy work.

Table 7.2: Physical/chemical properties of UK wheat straw

<table>
<thead>
<tr>
<th>Proximate analysis</th>
<th>Moisture content (%)</th>
<th>Ash content (%)</th>
<th>Volatile matter content (%)</th>
<th>Fixed carbon content (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>6.96</td>
<td>1.03</td>
<td>75.7</td>
<td>16.31</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Ultimate analysis</th>
<th>C (%)</th>
<th>H (%)</th>
<th>N (%)</th>
<th>O (%)</th>
<th>S (%)</th>
<th>Cl (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>47.5</td>
<td>5.88</td>
<td>0.35</td>
<td>46.28</td>
<td>0</td>
<td>&lt;0.3</td>
</tr>
</tbody>
</table>

On harvest straw typically has 15-25% moisture content with a lower heating value of around 18 MJ/kg. Previous work [53] indicated that straw is a typically high volatile, cellulose based material with volatile matter contents of 62-72% as received, 79.5-82% daf. Moisture contents of 6.2% - 15.1% generally reflect differences in history and storage.

Cereal straw has an ash content of 5-6% and has a low defomation temperature, resulting in propensity to slag and clinker during combustion. While Ca in straw may retain sulphur (e.g. in coal co-firing) this is not significant or reliable. Volatalisation of potassium at 800 C is likely to cause serious fouling problems in combustion boilers. [53] The Supergen results in table 2 are consistent with a low moisture content straw, but with a much lower ash content than expected based on the ETSU figures. This may be due to greater care having been taken in the harvesting process, as this is a sample prepared at field trial scale.

7.2 Feedstock origin
Straw is produced as a by-product when cereal crops are harvested. The harvesting process separates out the grain and straw, which is often mechanically gathered and
baled for storage and further use. Indicative straw yields from different cereal crops are given in table 7.3.

**Table 7.3: Straw yield for UK cereal crops**

<table>
<thead>
<tr>
<th>Cereal Crop</th>
<th>Straw yield (t/ha) [54]</th>
<th>Straw yield (t/ha) [55]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Winter wheat</td>
<td>3.9</td>
<td>3.5</td>
</tr>
<tr>
<td>Spring wheat</td>
<td>2.9</td>
<td>3.5</td>
</tr>
<tr>
<td>Winter barley</td>
<td>4.5</td>
<td>2.75</td>
</tr>
<tr>
<td>Spring barley</td>
<td>3</td>
<td>2.75</td>
</tr>
<tr>
<td>Winter oats</td>
<td>4.3</td>
<td>3.5</td>
</tr>
<tr>
<td>Spring oats</td>
<td>3</td>
<td>3.5</td>
</tr>
<tr>
<td>Triticale</td>
<td>3</td>
<td>3.5</td>
</tr>
</tbody>
</table>

In many cases there will be competing uses for straw. This may be on-farm e.g. as animal bedding or as a fuel to heat agricultural buildings or it may be sold on in an open market as bedding material or for other uses e.g. there is an increasing market for alternative uses of straw, such as renewable building materials. Generally barley straw is preferred for animal bedding, so that surplus material for the energy market is more likely to be wheat straw. Some straw is chopped and ploughed back into the field to return nutrients to the soil. Open burning of straw in fields is no longer permitted in the UK. Oil seed rape also produces straw, but this is more difficult to collect and is most often ploughed back into the ground.

The Biomass Task Force estimated in 2005 that the UK availability of straw for energy production was 3 Modt pa. [8] It stated that 9-10 Mtpa is actually produced; but much is recycled to livestock or ploughed back into the soil. Most of the surplus is in eastern counties. The resource is an essentially seasonal one as harvest occurs once a year for each crop. Bales may be stored uncovered; but this can be very wasteful, with deterioration accounting for up to 25% losses, mostly occurring Oct-Jan. [53] Simple sheeting of stacks can reduce losses substantially and proved to be the most cost-efficient method of long term storage.

Wheat production and therefore straw production are not evenly spread across the UK, but are concentrated in the east of England, from east Yorkshire down to east Anglia. [56]

When harvesting cereals there are generally only 15-30 working days available for gathering and baling straw, so baling capacity is crucial. [57] Very large stacks of Hesston bales are often left uncovered in fields in the UK.

**7.3 Technological issues associated with straw use**

Many straws have high levels of alkali metals, including potassium and also silica. This combined with the relatively high ash content for a biomass feedstock can give rise to problems during thermal conversion. During combustion there is a propensity for low melting point ashes to cause fouling and slagging problems with heat exchanger and grate surfaces. Some straws also contain high levels of chlorine, which can give rise to corrosion problems during combustion. Gasification of straw must address removal of chlorine compounds in the syngas and silica and potassium both have potential to foul gas turbines and engines if not removed. Pyrolysis liquid derived from straw can contain high levels of contaminant particles, owing to the high ash, silica and potassium levels in the feedstock.
Potassium content of straw is up to 3 times higher than that of wood chips and, when the ash is analyzed, potassium is found to be present in crystalline compounds with low melting points, which have sintered. [58] These constituents make straw a particularly difficult fuel to work with, for which special design measures have long been recommended and in some cases additives, such as magnesium oxide may assist in suppressing volatilisation of potassium. [59] Chlorine in the feedstock may also influence the fouling and slagging propensity of the ash. [60]

Specialized combustors exist which will allow whole bales of straw to be combusted. However, generally it is necessary to reduce the material in size. Where straw is required to be ground (e.g. in a hammer mill for co-firing) this will entail significant energy consumption. Figures for specific energy consumption for different grind qualities, moisture contents and feedstocks have been established experimentally. [61]

### 7.4 Environmental and ecological impacts

Utilisation of straw for energy purposes precludes its re-incorporation into soil. This reduces mineral return to the soil; although this could be compensated for by returning ash to the soil after combustion. However, it also impacts on soil organic matter content, which influences soil carbon content. Modelling work has shown that in a scenario where straw is removed from a field very other year long term decreases in soil organic carbon would range from 2.5-10.9\% of initial SOC after 50 years. The variation depends on a number of parameters, including soil, climate and productivity. [62]

### 7.5 Economics

The Farm Management Handbook [54] quotes prices of £25/t for wheat straw, £30/t for barley straw, £35/t for oat straw and £20/t for triticale straw.

Nix [55] notes that winter wheat straw has a value of £10-50/t according to region and season but mainly £20-25/t (£5 less in big bales). The average sale value according to Nix is £85/ha. Standing straw sold for baling can be valued from no value to £150/ha depending on crop, season and area of country/local demand. The national average is around £30/ha; double this in the west; at least treble in a season when straw is in short supply.

### 7.6 Social context

Straw is produced as part of normal arable farming activities, so there are no particular social consequences attached to its use for power generation, other than those generally associated with siting of a new biomass facility.

### 7.7 Prospects and Status

The UK currently has one large straw-burning plant: Elean in Cambridgeshire. This plant produces 38 MW electricity, consumes 200,000 tpa straw and is the largest straw-burning plant in the world. Biomass fuel to the plant is supplemented by 10\% natural gas to facilitate the relatively high steam conditions for a plant of this size.

A similar plant is planned at Sleaford in Lincolnshire, which would be rated at 40 MW. Planning and pollution control applications for this plant have been submitted to the relevant regulatory bodies.
Co-firing of straw in large coal-fired plants has, to date, been limited by transport constraints related to how far it is affordable to transport such a low bulk density fuel (120-150 kg/m³ for bales). [63]
8. Forestry residues

8.1 Background
The UK has 2,800,000 ha of woodland. This has increased significantly over the last century. In 1924 approximately 5% of the UK was wooded; in 2005 this was almost 12% and 700,000 ha of new woodland have been created in the last 30 years. In 2005, woodland covered 17 per cent of Scotland, 14 per cent of Wales, 9 per cent of England and 6 per cent of Northern Ireland. Most of this is traditionally managed to provide timber for a wide range of uses. [64]

The timber product generally comprises the main stem or trunk of the tree. This high value sawlog is the main economic driver for forestry operations. The top of the tree is generally not marketed, owing to small diameter and high degree of branching, as is the case with the live and dead branches, foliage, stump and roots. The distribution of biomass between these different components of the tree depends on the tree architecture, which is influenced both by genetics and environment. However, there a wide range of wood based material that could potentially be available for the woodfuel market in the UK, but are presently not recovered from forestry operations. These are considered separately below. [65]

8.2 Feedstock description
Existing forestry activities exist to supply existing markets for timber. However, there is the potential to supply some material to the energy market. This material can be divided into the following categories:

- Poor quality final crops – These are large enough to be used for timber, but are of such poor form that they are normally left on site or may sometimes be cut for firewood.
- Small roundwood – these are small stems cleaned off side branches with a diameter of typically 7-14cm, based on common practices in the UK
- Harvesting residues – These include the tips of the stems (top of the tree) and side branches

The stump and root wood also contains biomass, but recovery of this is technically more difficult and unlikely to be economic.

It should be noted that, under present practices, harvesting residues are generally left on the forest floor. As they decompose these return nutrients and organic matter to the soil. There is some concern that [66] removing these residues may impact on future soil growth and quality, impacting on the sustainability of the fuel supply. The extent to which this is likely to be a problem is not presently clear, although some countries, such as Sweden, already actively require recycling of wood ash to the forest to minimise the impact. However, in the UK the present requirement is that whole-tree harvesting should not be practised where it is likely to have negative effects.

It should also be noted that there are competing markets for this material in the UK. In particular the 7-14cm stemwood (small roundwood) is unlikely to be readily available for an energy market. Experts in the area have concluded that only 10% of the small roundwood, but 100% of the poor quality stemwood, stem tips and branches are likely to be available [67]
As harvested, forestry residues may have a moisture content anywhere from 30% to 65% or more.

**8.3 Feedstock origin**
The feedstock originates from harvesting of either coniferous or broadleafed species in UK woodlands.

**8.4 Environmental and ecological impacts**
European forests, including those in the UK, comprise planted and natural forests; the management of which is continuously evolving because of developing knowledge and changes in public attitudes and policy. They are required to provide wood and fibre for society, but also to provide environmental services (not least carbon sequestration), biodiversity conservation, ecological functions, recreational facilities etc. In order to maximise these benefits the woodlands need to be actively managed, including thinning and regeneration. In some areas of the UK 50% of woodland is believed to be poorly managed [67] and regeneration of a woodfuel industry could help to stimulate this.

The potential environmental impacts of extracting forestry residues are diverse and site specific, but include the following:

- Preservation of sustainable forest productivity
- Protection of soil structure and the soil resource
- Maintenance of water quality, through the control of sediment transport
- Maintenance of bio-diversity
- Carbon sequestration
- Woodland amenity, access

The extent to which any of these criteria are impeded by harvesting of residues depends on the local terrain, climate and tree species. A thorough survey of these issues for the UK was carried out in 2004 [68] and found that only a proportion of forestry residues could sustainably be removed from UK forests. This proportion varied regionally; with the upland forestry in the north and west of the UK being generally less suitable than the lowland forestry in the south. As part of this work actual percentages of the forested land that were suitable for residue harvesting were calculated and at national level the percentages were broadly consistent with the separate woodfuel resource assessment which provided the fuel availability data in the tables below.

**8.5 Production**
At present whole tree harvesting is not practised in the UK. Whole stems (trunks) are harvested for sawlogs and small roundwood is frequently harvested. Where this is done it is simply left to dry in sheeted piles on bearers until required. Harvesting of the thinner residues would require alternative techniques, such as in-situ chipping or baling. There has been little direct UK experience of these and so their applicability is difficult to assess at this stage.

Green bundles have been shown to contain typically 50% moisture, but when stacked and covered with paper these can dry to 25%. A typical bundle would be 3.2 m x 68 cm (1.16 m³), weighing 550 kg fresh or 367 kg when dried to 25% moisture. In Sweden road transport of bundles by a timber truck involves a maximum load of 39 t.
or 114 m³. [69] Note this study also gives further information on economics and transport logistics.

8.6 Economics
Assessments of supply chains for forestry residues in Belgium have concluded that the costs could range from 58 to 120 euro/odt. The lower prices were obtained for small and large scale loggers. Higher prices relate to small scale loggers or farmers working on a more opportunistic basis. [70]

8.7 Social context
Only 20% of the UK population lives in rural areas and they have suffered a severe drop in income in recent years. Rural development is a key component of the push for sustainable forest management in the UK. Farmers own 20% of UK woodland and the actual area of farm woodland has almost doubled in the last 20 years, being responsible for an estimated 5,000 jobs in the UK. [67] A woodfuel market from sustainably managed farm woodlands could therefore contribute significantly to rural employment and development.

8.8 Status and prospects
A thorough review of the UK woodfuel resource in 2004 concluded that the current annual production of potential operationally available biomass was 5.63 million odt, broken down as in table 8.1.[71]

Table 8.1: Present annual production of forestry material in UK

<table>
<thead>
<tr>
<th>Present annual production (odt pa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>18 cm+ stemwood</td>
</tr>
<tr>
<td>16-18 cm stemwood</td>
</tr>
<tr>
<td>14-16 cm stemwood</td>
</tr>
<tr>
<td>7-14 cm stemwood</td>
</tr>
<tr>
<td>Poor quality stemwood</td>
</tr>
<tr>
<td>Tips</td>
</tr>
<tr>
<td>Branches</td>
</tr>
<tr>
<td>Foilage</td>
</tr>
<tr>
<td><strong>Total</strong></td>
</tr>
</tbody>
</table>

Source: 3

3,610,640 tpa of this material is within the private sector; the remainder within the public sector (Forestry Commission owned). Forecasts have been carried out of the equivalent amount of material going forward, but also applying recovery factors to allow for the facts that forecasting recoverable material is dependent upon political, technical and commercial factors. In recognition of this the following predictions of potential UK resource have been made.

Table 8.2 shows that the availability of forest residues at around 1.9 M tpa is likely to be sustained in the long term, with small potential increases. This assessment does not take account of potential competing markets for woodfuel and this accounts for significant quantities of the roundwood. Therefore, when this is taken into account revised estimates of availability are around 800,000 tpa. [67]
Table 8.2: Projections of annually available forestry residues in the UK private and public sector

<table>
<thead>
<tr>
<th>Year</th>
<th>Public 7-14cm stems</th>
<th>Public Poor quality stems</th>
<th>Public Branches</th>
<th>Public Tips</th>
<th>Public Foilage</th>
<th>Public Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>2003-6</td>
<td>471,928</td>
<td>10,370</td>
<td>94,438</td>
<td>40,366</td>
<td></td>
<td>1,858,674</td>
</tr>
<tr>
<td></td>
<td>560,472</td>
<td>278,602</td>
<td>21,124</td>
<td>315,694</td>
<td>65,680</td>
<td>1,927,644</td>
</tr>
<tr>
<td>2007-11</td>
<td>466,744</td>
<td>9,467</td>
<td>99,395</td>
<td>41,876</td>
<td></td>
<td>1,963,597</td>
</tr>
<tr>
<td></td>
<td>583,430</td>
<td>283,400</td>
<td>20,744</td>
<td>348,406</td>
<td>74,182</td>
<td>2,015,150</td>
</tr>
<tr>
<td>2012-16</td>
<td>461,387</td>
<td>9,047</td>
<td>100,101</td>
<td>41,904</td>
<td></td>
<td>1,990,348</td>
</tr>
<tr>
<td></td>
<td>594,603</td>
<td>274,536</td>
<td>20,456</td>
<td>381,810</td>
<td>79,753</td>
<td>1,960,008</td>
</tr>
<tr>
<td>2017-2021</td>
<td>447,679</td>
<td>8,595</td>
<td>101,014</td>
<td>41,418</td>
<td></td>
<td>1,910,403</td>
</tr>
<tr>
<td></td>
<td>555,696</td>
<td>263,288</td>
<td>18,939</td>
<td>384,156</td>
<td>79,455</td>
<td>1,900,240</td>
</tr>
</tbody>
</table>

8.9 Conversion process

Forestry residues would likely be chipped prior to conversion for bioenergy. They could then be used for the same purposes as any other lingo-cellulosic material. The most likely routes are combustion, gasification or pyrolysis to provide heat or electricity. Conversion to biofuels is only possible via second generation technologies.
9. Forestry related material

In addition to the forestry residues discussed above there are other potential woodfuel sources in the UK related to forestry or the timber industry. The main significant ones are arboricultural arisings, which result from management of trees grown in urban settings and sawmill materials, which are byproducts of the timber utilisation process.

Sawmill co-product can take the form of chips, sawdust or bark. It should be noted that there are substantial competing markets for the sawmill byproducts, including fibre board manufacture and other similar industries. However, it has been estimated that up to 86,000 tpa could be available in the UK based on current activity.

Arboricultural arisings are a particularly promising source for the UK, since trees and woodlands are managed intensively in urban areas. This includes harvesting and pruning particularly by local authorities and arboricultural contractors. This material is concentrated, collected and cannot be left by the roadside where trees are felled – it must be disposed of, often with associated cost, so it is a particularly practical resource. A study has estimated that 341 ktpa could be available for woodfuel use, even in the presence of competing markets. The characteristics of this material are similar to the forestry residues, described above.
10. Wood pellets

10.1 Background
Pellets are compressed, densified pieces of wood, which can be derived from a variety of sources, including agricultural residues and energy crops, but are most commonly made from virgin wood. In general pellets are produced by compressing fine sawdust in a die, so that the heat/pressure generated melts the lignin in the pellets and binds the particles together. Sometimes binders may be added, although not generally for domestic use. [72]

As noted in the section on forestry, up to 86,000 tpa sawmill co-product could potentially be available to a UK woodfuel market each year. This material is ideal for manufacture of pellets and there are a growing number of businesses in the UK manufacturing pellets for their own use and open-market trade. The main advantages of pellets over woodchips or other forms of woodfuel are that they are more convenient for the end-user in terms of handling properties and fuel consistency. This decreases the likelihood of reliability problems, such as blockages in feed handling systems. They are therefore particularly advantageous for smaller biomass systems, where knowledgeable technical operators may not be present and are seen by many as key to expanding the domestic use of woodfuel.

Other advantages of using pellets include storage characteristics that are generally better than unprocessed feedstocks (reducing degradation issues), increased density (reducing storage volume requirements and enabling more efficient transport) and less dust arisings from handling, storage and transfer.

However, these benefits are to be set against the higher cost of pellets and the energy consumed in the production process, potentially reducing the extent of greenhouse gas savings.

10.2 Feedstock description
In Austria, Sweden and Germany, where pellet markets are larger, specific standards exist for pellet characteristics. This is not the case in the UK. However, in 2000 British Biogen published a good practise guide, which effectively specified some of the parameters usually included in standards. [72] At present European CEN standards are under development for pellets, which cover a range of possible pellet sizes etc. [73] The main parameters covered in the standards are described in the left hand column of table 10.1. While a range of values for each of these parameters exists typical classifications are given in the right hand column, by comparison to the pre-existing British good practise guide [72] and other assessments of standards. [74]

The national Biomass Energy Centre quotes typical bulk costs of £140-180/t supplied in the UK. [75]

Pellets for domestic purposes are generally made from virgin and clean wood, sized 5-20mm, although slightly larger sizes may be used for commercial markets. Ash contents may vary from 1% (premium), 3% (standard) to 6% (high ash). Typical bulk density is 600 kg/m$^3$. [72]
Table 10.1: Typical characteristics of wood fuel pellets

<table>
<thead>
<tr>
<th>Mechanical durability</th>
<th>M97.5 – at least 97.5% of pellets must survive test</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size</td>
<td>D06: diameter ≤6mm and length ≤5 x diameter</td>
</tr>
<tr>
<td></td>
<td>D08: diameter ≤8mm and length ≤4 x diameter</td>
</tr>
<tr>
<td>Fines</td>
<td>F1.0 &lt;1%</td>
</tr>
<tr>
<td></td>
<td>F2.0 &lt;2%</td>
</tr>
<tr>
<td>Moisture content</td>
<td>M10 &lt;10%</td>
</tr>
<tr>
<td>Ash content</td>
<td>A0.7 &lt; 0.7% - most common for domestic/small boilers</td>
</tr>
<tr>
<td></td>
<td>A1.5 &lt;1.5%</td>
</tr>
<tr>
<td></td>
<td>A3 &lt;3.0%</td>
</tr>
<tr>
<td></td>
<td>A6 &lt;6.0%</td>
</tr>
<tr>
<td>Calorific value</td>
<td>Not specified in CEN, but other existing European national standards range from 16.9 – 19.5 MJ/kg; UK good practice has E4.7 – at least 4.7 kWh/kg</td>
</tr>
</tbody>
</table>

10.3 Feedstock origin

There are currently at least 19 pellet production facilities in the UK. [75] The industry has grown from having no production capacity in 2002 to having 96,000 tpa capacity in 2004. [73] In terms of the domestic market 5,000 tonnes were produced in the UK in 2004, but only 2,000 tonnes were used, the remaining 3,000 tonnes being exported. [73]. The vast majority of pellets in the UK are consumed at UK power stations. Utilising wood-based material allows electricity producers to claim renewable obligations certificates (ROC’s) and the hardness and grindability characteristics of pellets are better-suited to the mills installed at most large pf stations than more conventional forms of biomass. In 2005 266,000 tonnes of pellets were consumed at UK power stations, of which 52,000 tonnes were domestically produced; the remainder being imported.

10.4 Environmental and ecological impacts

In the case of fresh, wet sawdust the energy required to dry the sawdust and produce pellets is approximately 10% of the pellets own energy. If the sawdust is already dry it is approximately 2%. [76]

Detailed work on pellet production and supply carried out under an EU Altener project used the following logistic figures for pellet systems:

Table 10.2: Characteristics for pellet transportation by truck

<table>
<thead>
<tr>
<th>Truck capacity</th>
<th>40</th>
<th>Tons</th>
</tr>
</thead>
<tbody>
<tr>
<td>Truck capacity</td>
<td>130</td>
<td>m³</td>
</tr>
<tr>
<td>Average speed</td>
<td>65</td>
<td>Km/h</td>
</tr>
<tr>
<td>Fuel use (diesel)</td>
<td>45</td>
<td>l/100km</td>
</tr>
<tr>
<td>Km-costs</td>
<td>0.85</td>
<td>Euro/km</td>
</tr>
</tbody>
</table>

Additionally loading and unloading costs are around 0.50 euro/m³. This results in the following specific costs for different cargo types in euro/ton.
Train transport was considered to have capacity of 2500 m$^3$, 1000t with an average speed of 75 km/h, with the following costs:

**Table 10.3: Specific costs of train transport, including transfer, in euros/tonne**

<table>
<thead>
<tr>
<th>Distance</th>
<th>Pellets</th>
</tr>
</thead>
<tbody>
<tr>
<td>500 km</td>
<td>9</td>
</tr>
<tr>
<td>1000 km</td>
<td>12.8</td>
</tr>
<tr>
<td>1500 km</td>
<td>16.7</td>
</tr>
<tr>
<td>2000 km</td>
<td>20.5</td>
</tr>
</tbody>
</table>

Ship transport has the following characteristics: 22,000 tonnes, 30,000 m$^3$, 65 km/h and heavy fuel oil use of 4 tons/100km. A large share of the total costs for sea transport occur in the harbour related to loading/unloading (2.6 to 4.3 euro/ton) and port charges.

**Table 10.4: Specific costs of sea transport in euro/ton**

<table>
<thead>
<tr>
<th>Distance</th>
<th>Pellets</th>
</tr>
</thead>
<tbody>
<tr>
<td>1500 km</td>
<td>12</td>
</tr>
<tr>
<td>10000 km</td>
<td>21</td>
</tr>
</tbody>
</table>

### 10.5 Production

Pellet production generally requires a supply of dry sawdust of a consistent moisture content and uniform particle size. This processed sawdust is then forced or pressed through holes in a rotating die. The pressure causes the wood to heat up, briefly liquefying the lignins and resin in the wood, which act as a glue and bind the pellets together. The extruded pellets are cut to length as they emerge from the die. They are then allowed to cool before being sold in bulk or bagged for delivery. [76]

Typical production capacity is in the range of 3-10 t/h. [77]

Where incoming raw material has not already been dried this will be the first stage in the pelletisation plant. [78] Wet sawdust from mills typically has a water content of 55% wet basis. [79] This would first be dried using steam in a tube bundle drier, drum drier, belt drier or possibly a fluidised bed drier. This step represents one of the most significant consumptions of energy in the pellet production process. The actual consumption of energy can vary substantially depending on the drying technology chosen e.g. superheated steam driers incorporating energy recovery for another purpose can be particularly efficient. [79]

After drying the material is generally ground (most often in a hammer mill). [79]

Following grinding the pellets are pressed in either a ring die or flat die pellet mill. There is generally further steam consumption associated with the pellet production process. [79]

At small plants there may be no other processing of the pellets, but at larger facilities there usually follows a counterflow cooler prior to storage. [79]

Storage on site is often in a simple silo of relatively low capacity (less than 10% of annual production). [79]

### 10.6 Economics

Small-scale pellet machines are available with an output of 200-300 kg/h, costing £50,000 to £150,000, depending on the level of automation and quality required. [76]
Specific investment costs vary, but the average is 100 euro for each tonne per year capacity. [77]

Typical costs to consumers in the UK have been cited as £140-180/tonne. [75] This is not entirely consistent with a European project, which collated cost data and cited UK figures as 300 euro/tonne for small bags and only 150 euro/tonne for large bulk deliveries. [73]

The production costs for wood pellets are mainly influenced by the raw material costs and, in the case of using wet raw materials by the drying costs. Depending on the framework conditions these two parameters can contribute up to one-third of the total pellet production costs. Other important parameters influencing the pellet production costs are the plant utilisation (number of shifts per week) as well as the availability of the plant. For an economic production of wood pellets at least three shifts per day at 5 days per week are necessary. An optimum would be an operation at 7 days per week. A plant availability of 85-90% should be achieved, but a profitable enterprise is possible at small scales (a few hundred tonnes per year) as well as large (10,000 tonnes per year).

10.7 Social context
One market for sawmill by-products is wood shavings for horse-bedding. Removing sawdust from the shavings increases quality and price by £1/bale, but there is no market for the sawdust. It could be used to produce pellets. [78]

10.8 Status and prospects
Work carried out under an Altener project in 2005 examined prospects for international pellet trade in Europe. In particular it looked at the economics of producing pellets in southern Europe (Spain, Greece and Italy) and exporting to northern European countries, including the UK. This found that imported pellets could be delivered at a cost of 135-175 euro/tonne, compared to a UK indigenous market price of 170 euro/tonne. This suggests that it is very likely that pellets may be imported from elsewhere in Europe to the UK market, purely on economic grounds.[73]
11 Short rotation coppice

11.1 Feedstock description
Short rotation coppices are fast-growing trees, whose growth is accelerated by severe cutting back early in the growth cycle. This causes coppicing – propagation of multiple shoots from the stem, which allows faster growth. After a number (typically 2-5) of years the plantation is completely cut back again for harvesting of the whole tree. Growth then resumes so that after the same number of years (another rotation) a similar quantity can be harvested again. Plantations are expected to continue productivity for 20 years or more. The stems are generally sufficiently small diameter that they can be harvested by specially designed mobile harvesters and comminuted in the field for storage as chips.

11.2 Feedstock origin
Willow is the most common choice for coppice plantations in the UK and is native to the northern hemisphere, growing particularly well in wet, cool climates. [80] It is grown mainly in the northern parts of the European Union and has been particularly grown in Sweden via research programmes since 1975 and commercially since 1991. An average yield of 8-10 odt/ha is expected in Sweden and should not be very different under UK conditions. [81]

11.3 Environmental and ecological impacts
Recent work in the UK focused on identifying key environmental impacts of large scale deployment of crops for bioenergy. This concluded that SRC crops offered positive effects on soil properties, biodiversity, energy balance, greenhouse gas emissions, carbon footprint and visual impact compared to arable crops. However, benefits were less apparent when compared to unimproved grassland or set-aside land. There is potential for negative hydrological effects, but these can be minimised by appropriate catchment management. Generally it was found that SRC could offer significant benefits for the environment and these were clearer than for grasses such as miscanthus, but only if landscape-scale issues were effectively managed and the whole chain of crop growth and utilisation were placed within a regulatory framework where sustainability was a central driver. [82]

The nature of SRC growth can result in significant visual impact. Rowe et al. [82] identified the main concerns as obscuring of landscape features, obstruction of views, impacts on scenic quality and rapid changes in visual appearance caused by harvesting. These impacts can be minimised by adjusting the scale and shape of plantations to suit landscape features and complementary planting of shrubs or native trees and in some cases the plantations may serve to add visual interest to landscapes.

Rowe et al. [82] also reviewed the evidence relating to soil organic carbon changes with energy crops and concluded that conversion of arable land to SRC will result in an increase in carbon sequestration, possibly 0.55-0.83 t C/ha pa, but eventually soil carbon equilibrium will be obtained, with no further increases and it is not certain how long this will take.

Borjesson [83] analysed nitrogen leaching from energy crops in Sweden and concluded that a 50% reduction of nitrogen leaching over 60% of Swedish arable land would be possible by the establishment of SRC and miscanthus plantations, with
further benefits if these were used as buffer strips along watercourses. Similar benefits could be achievable in the UK.

Establishment of SRC is generally considered to reduce susceptibility to soil erosion, owing to the extensive rooting system and absence of annual tillage. There were some concerns that erosion problems might occur during the establishment stage, but these have not been sustained. [82]

11.4 Production

The production regime described here was used for modelling in the Supergen 1 consortium and is representative of typical known practical experience with SRC willow crops. [84] The establishment period typically starts with an application of herbicide to kill perennial weeds followed by the cultivations required to obtain suitable planting conditions, typically one pass with both a plough and a rotary power harrow. SRC is planted as lengths of willow cane, using a specialist planter, frequently by a planting contractor. After planting rolling and weed control is carried out in the establishment year, with cut back just above ground level with a tractor mower at the end of year 1.

During the production period the requirements of the crops are very low compared with conventional arable crops. SRC is usually harvested every three years, however the cutting cycle can vary between two to five years. The harvesting is usually done with a self propelled forage harvester with a specialist SRC header; the header cuts the crop and feeds it into the forage harvester, which chops the wood into chips. The chips are blown from the harvester into a trailer running alongside or behind the harvester, and the trailers then transport the chipped material to the storage area, where again, a rough terrain forklift truck may be used to produce higher stacks. [84]

11.4.1 Yield

Yield of SRC crops is affected by a large number of environmental variables, including ground conditions, weather conditions, nutrient application, weed infestation etc. This results in significant variations in yield from one region to the next and even from one field to the next. The NNFC C quotes UK yields of 25-30 odt/ha for first harvest and 30-35 odt/ha for subsequent harvests every 3 years.

11.4.2 Agrochemical applications

Fertiliser

There is only limited experience and knowledge of the long-term fertilizer and herbicide requirements of the crops during the production period. Research evidence can be contradictory, and industry practice is based on only young plantations. At present herbicide requirements seem likely to be once every three years for SRC i.e. after each harvest. Fertiliser is not routinely applied to many SRC plantations in the UK, but a number of sites apply treated waste water or sewage sludge, which provides a source of nutrients.

Other agrochemicals

Glyphosate is generally applied during soil preparation prior to planting and at the end of the plantation life. Post-emergence herbicide is applied after planting and there is generally little other requirement for regular agrochemical treatments. The main pests to affect the crop are beetles belonging to the Chrysomelidae and two species of aphid. The major disease threat is rust, the risk of pest and disease problems can be
minimised by planting a mix of genetically diverse varieties, rather than a monoculture.

### 11.4.3 Proposed agronomic regime for modelling purposes.

A potential agronomic regime that could form the basis for modelling purposes is given in table 11.1.

<table>
<thead>
<tr>
<th>Energy crop production</th>
<th>Ground preparation</th>
<th>Establishment</th>
<th>Harvesting &amp; restoration</th>
<th>Energy crop processing, storage &amp; provision</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Glyphosate application</td>
<td>Ploughing</td>
<td>Secondary cultivation</td>
<td>Harvesting &amp; direct chipping</td>
</tr>
<tr>
<td></td>
<td>Planting</td>
<td>Rolling</td>
<td>Herbicide</td>
<td>1sr yr cutback</td>
</tr>
</tbody>
</table>

### 11.5 Economics

A recent study in Ireland found that gross production costs of SRC willow (based on a yield of 10 odt/ha) were 31-46 euro/tonne dry matter. Establishment was shown to be the largest component of production costs in this work, although drying and storage could be significant for some supply strategy options. [85] This study showed the margins obtainable on farm for willow production could provide annualised gross margins greater than 200 euro pa/ha (comparable with conventional farming activities) at a price of 100 euro/tdm. Positive margins were achievable at 70 euro/tdm (which is commonly achieved in England), but were not as attractive compared to conventional farming activities. At 2008 – 10 agricultural commodity prices the comparison is much less favourable.

### 11.6 Social context

It is often argued that production of energy crops can provide an alternative income for farmers and aid rural diversification. Recent economic studies cited above support the notion that it is possible to make a profit from production of willow at biomass prices that are achievable on the open market. However, the main barrier is the high up-front establishment cost and the lack of regular income in the early years.

One attraction to some growers of SRC cultivation is that it generally requires little management and attention between planting and harvesting. This may be an attraction to landowners who desire a moderate return from their land, but do not wish
to be heavily engaged in general farming activities. The annualised labour requirements for willow are certainly lower than for conventional arable farming and this is obviously not going to create additional farming jobs where SRC is planted into arable land. Job creation is more likely to be related to transportation and the establishment of local power plants in rural communities.

11.7 Status and prospects
Research into short rotation coppice (SRC) as a biomass crop has been on-going in the UK since the mid-1980’s. Large scale commercial plantings began in the mid-1990’s with around 1500ha established for the ARBRE project [86]. Since 2001 the Energy Crops Scheme has provided establishment grants for SRC and Miscanthus grown in England to supply biomass for the energy market, and under the scheme 1180 ha of SRC and 3358ha of Miscanthus were planted between 2001 and 2006 [84] Of the SRC planted under the scheme the majority was willow, with just 5 ha of poplar planted in 2006. [84]

Some SRC is supplied for co-firing, but we believe an increasing proportion is now going for small scale heat production. In addition to the establishment grants, the only other financial incentive for growers is an EU payment of 45 Euros/ha/yr for energy crops; however, a proportion of this payment is taken by the crop processor.

For various reasons the price of UK cereals has increased dramatically and unexpectedly from summer 2007. For this reason, it is unlikely that the expansion of the biomass crop area will continue without equivalent increases in the unit price of biomass, or other financial incentives for growers.

So far, we believe the majority of UK biomass crops have been planted into arable land. This is partly because the low incomes of arable crops in recent years have lead growers to look for alternative crops. However, with arable crop incomes increasing, if the area of biomass crops is to expand in line with government expectations, it seems likely that an increasing proportion will be planted into grassland.
12. Short rotation forestry

12.1 Feedstock description
Short rotation forestry involves planting a site with trees, allowing them to grow and then harvesting the tree when it has reached a pre-determined size – typically 10-20 cm diameter at breast height. The main differences between short rotation coppice and short rotation forestry are that with SRC there is a requirement to cut back the energy crop typically one year after establishment. With SRF there is no such requirement. This means that the trees do not produce the multitude of shoots that allows SRC its fast growth and higher yield, but also the the ratio of wood to barks is higher for SRF than SRC. The time period required to obtain harvestable material from SRF depends on the tree species, but can typically range from 8-20 years. [87] Conventional forestry rotations in Britain are 40-150 years.

The aim of SRF harvesting is to harvest stem wood only, leaving bark and residues on the forest floor to return nutrients to the soil. [88]

12.2 Feedstock origin
Some of the tree species proposed for short rotation forestry are familiar within the UK, such as poplar, sycamore and ash, though others, such as eucalyptus, are less familiar.

The most widely grown short rotation forestry species worldwide is eucalyptus, which can achieve yields in excess of 30 t/ha pa over a 7 year rotation. 10 million hectares of eucalyptus exist in worldwide plantations, much of it managed on a short rotation basis in China, South Africa, Chile, Portugal, Brazil and India to produce wood pulp. Generally it grows best in temperate or tropical zones. In more temperate climates, such as that of the UK poplar and willow may be grown on a 6-10 year cycle. [89]

Willow can be grown for short rotation forestry, where it is not coppiced, in which case the rotation period is 8-10 years, with an expected yield of around 6-8 tpa, based on experience in Sweden. [90]

There is also experience in Sweden of growing poplar and aspen with higher yields of 10-15 t/ha, but with a much longer rotation of 30 years or more. Similar yields could be expected for mixed deciduous forests of birch, alder, aspen, poplar, but again 30 year rotations are typical.

A study considering the UK potential for short rotation forestry in 2006 considered 10 species: 4 native ones (alder, ash, birch and poplar), one naturalised species (sycamore) and five non-native species (three fo eucalyptus and 2 of southern beech). [88]

12.3 Environmental and ecological impacts
Short rotation forests are even-aged and spaced plantations that are regularly felled, so they do not contain the variety associated with natural forests, nor are they as useful for recreational purposes and less aesthetically pleasing. Therefore, when compared with natural forests they have few ecological benefits, but are an improvement when compared to agricultural land. [89]
Short rotation forests require minimal management during the growing phase and there are no particular impacts arising. The general regime is similar to that for short rotation coppice, except that there is no cutting back or thinning of the plantation in the early years of growth and harvesting is generally whole tree harvesting after a longer period (8-20 years). Harvesting requires felling machinery, as commonly used in forestry operations, rather than the more agricultural equipment used for coppice regimes, where the stem diameter is generally smaller. Generally there is no fertilisation and other agrochemical interventions are as necessary, based on predominance of pest and/or disease.

A study on the potential for short rotation forestry in the UK by the Forestry Commission in 2006 concluded that there were no serious issues relating to biodiversity, soils, hydrology, pests, disease and landscape that would rule out short rotation forestry as a potential land use. [88]

12.3.1 Energy balance and greenhouse gas impact
A study based on 4 year rotations, with no coppicing at some sites in Belgium calculated overall greenhouse gas benefits when providing heat or electricity and found that marginally greater benefits were obtained for birch and poplar, compared to willow; while maple performed significantly worse.

A Forestry Commission study calculated that emissions related to fencing, fertiliser manufacture and application, weeding, thinning, harvesting and removal of timber from site were 0.674 tonnes CO2/ha/yr; while carbon sequestration was in the region of 200-350 tonnes CO2/ha/yr.

12.3.2 Impact on habitat and biodiversity
Short rotation forestry results in areas of land stocked with trees of a similar age, large areas of which are regularly clearfelled and managed in such a way that there is no dead or dying timber left to accumulate. This reduces the attractiveness of the habitat for some species. However, overall the biodiversity is different to other forms of land use (say grassland with hedges), but comparable in terms of quantity and variety. It is not as attractive as natural forest, but is generally better than agricultural farmed land.

The Forestry Commission 2006 study reported that three key potential areas of impact (biodiversity, hydrology and landscape) were closely correlated so that good practice with one tended to be positive or neutral to others. [88]

Potential negative impacts (high water use, limited biodiversity, visual impact) were found mainly for more productive species, giving rise to some concern that economic decisions may result in higher environmental impacts.

12.3.3 Risks associated with agrochemical use
Agrochemical use is minimal and so the risks are very low.

12.3.4 Impact on water courses
Agrochemical use is minimal and so the risks related to nitrates are very low. There is potential for positive impact on water systems, where contaminated water or leachate from landfill operations may be absorbed by tree growth and heavy metals taken up by the biomass.
There are serious potential impacts from SRF on hydrology in some areas of the country, particularly when climate change predictions are taken into account. There is therefore potentially a need to control planting where it could affect critical water supplies.

### 12.3.5 Impacts on soil

Impacts on soil are generally positive with increased levels of leaf litter having potential to restore organic matter to soils which were previously under arable cultivation.

SRF will be no more damaging to archaeology than arable cropping or commercial forestry and critical sites, such as very wet ones will not be used.

### 12.3.6 Byproduct impacts

There are no significant byproducts arising.

#### 12.4 Production

##### 12.4.1 Yield

Yields vary between species and site and there has been relatively little experience in the UK. In warmer climates, with appropriate species, yields much higher than those for European agricultural crops can be achieved – up to 30 t/ha being reported. However, data Belgium reports much more modest yields of 4 t/ha for 4 year rotations [91] with species that could flourish in the UK and up to 15 t/ha in Sweden, but with a rotation of 30 years or more. [90]

A forestry Commission study in 2006 projected the following potential yields for different species:

<table>
<thead>
<tr>
<th>Species</th>
<th>Rotation period (years)</th>
<th>Yield (dry t/ha per rotation)</th>
<th>Yield (dry t/ha pa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alder</td>
<td>20</td>
<td>100</td>
<td>5</td>
</tr>
<tr>
<td>Ash</td>
<td>20</td>
<td>148</td>
<td>7.4</td>
</tr>
<tr>
<td>Birch</td>
<td>20</td>
<td>100</td>
<td>5</td>
</tr>
<tr>
<td>Poplar</td>
<td>14</td>
<td>78</td>
<td>5.6</td>
</tr>
<tr>
<td>Sycamore</td>
<td>20</td>
<td>140</td>
<td>7</td>
</tr>
<tr>
<td>E. gunni</td>
<td>12</td>
<td>108</td>
<td>9</td>
</tr>
<tr>
<td>E. nitens</td>
<td>8</td>
<td>120</td>
<td>15</td>
</tr>
<tr>
<td>Nothofagus</td>
<td>12</td>
<td>142</td>
<td>11.8</td>
</tr>
</tbody>
</table>

##### 12.4.2 Agrochemical applications

Generally no agrochemicals are applied during growth unless for particular reasons of pest or disease.
12.4.3 Proposed agronomic regime for modelling purposes.
The establishment regime is broadly similar to that for short rotation coppice establishment, with no cutback phase. Fertiliser or organic solids may be applied after the first year. The harvesting is much more heavy duty.

12.5 Economics
The main economic differences between short rotation forestry and short rotation coppice systems are:

- No cost for cutback after year 1
- Delayed income from the plantation for 8-30 years
- Larger cost attached to more significant harvesting activity, but executed less often

The Forestry Commission report of 2006 estimated costs for establishment as £2841/ha or £2,145/ha if fencing is excluded. These costs are fairly independent of species. [88] However, the variation in productivity between the species means that the IRR obtained by the grower is much more sensitive to species.

If revenue from the purchaser of the crop is assumed to be £40/odt; this is approximately £20/wet tonne and, excluding transport cost, results in revenue to the grower of around £10 per wet tonne. At this price level obtaining an IRR of 10% for the enterprise requires initial grant funding at establishment of £1,950 to £2,550. This is substantially higher than the establishment grant available for short rotation coppice. It is possible to improve the economics by using coppice rotations beyond the first harvest; but this requires a much longer productive/investment period of up to 60 years.

12.6 Social context
As noted below, it is considered unlikely that there would be a significant move towards short rotation forestry on privately owned land. Therefore issues related to farmer’s income are not particularly relevant. One issue that is frequently raised in relation to short rotation coppice is the potential visual impact of large developments. This would be even more the case with short rotation forestry, with larger trees covering significant areas of land for long periods.

12.7 Status and prospects
There has not been any substantial effort at short rotation forestry in the UK, so yields and the best species to choose remain uncertain.

In general short rotation forestry is a very long term investment, with returns not being experienced until a large number of years after the initial outlay. In the current climate in the UK the risks associated with making such an investment with no prospect of return for so long are such that it is unlikely that it would be undertaken by private landowners. However, around 50% of the UK’s woodland is in public ownership and it is possible that a shift in the strategy for publicly owned land could facilitate some of this being used for short rotation forestry.
13. Switchgrass (*Panicum virgatum*)

13.1 Feedstock Description

Switchgrass is a perennial, cool-season, seeded grass, native to the US, growing up to 2.5m tall. It has a C4 photosynthetic pathway and is therefore an efficient user of nitrogen and water. In the US, switchgrass is considered the most valuable native grass in a range of areas; primarily used for forage production and more recently identified as the most promising species for development into a biomass crop [92]. In North America it has long been used for soil conservation and used in mixtures for riparian buffer zones.

There are two distinct ecotypes of Switchgrass, Lowland and Upland. Lowland types have a more bunch like growth, grow taller, flower and mature later under UK conditions. Upland ecotypes have a much more dense sward and are more likely to reach full maturity (senescence) in the UK. [93]

13.2 Background

Experience of the crop in the UK is limited and much of the detailed, long-term knowledge originates from experience in the US. In 1992, the potential of the crop as a possible energy crop for the UK was demonstrated at Rothamsted Research. [94] Later in the 90’s, a European research team investigated the production of the crop across several European countries and produced a management guide to the selection, establishment and production of the crop. [28].

Breeding programmes have been developed in the US and more recently Canada. The original purpose of these programmes in the US was for forage and these have now been adapted for use in biomass systems, fermentation and combustion. In Canada, crop has been breed for energy, primarily combustion for heat. [95, 96] Breeding programmes in Europe have yet to be developed.

Some commercial plantations of the crop have been established in the UK but this is currently only a very small area with one or two growers. Calculating the exact figures for the area of switchgrass sown in the UK is difficult as the crop does not receive establishment support grants from the government.

13.3 Feedstock Origin

The native habit of switchgrass originally included the prairies, open woods, brackish marshes and pine-woods of most of North America except for the areas west of the Rocky Mountains. [92] It is indigenous to North America and is found from Mexico into Canada but it does not occur naturally above 55oN lat. It is also found in South America and Africa where it is used as a forage crop. [27] Unlike miscanthus, switchgrass can be grown from seed rather than rhizomes, making it much cheaper to establish. [97].

13.4 Production

Switchgrass is a seeded grass and is sown in April/May using standard farming equipment. Perennial weeds are eliminated by glyphosate prior to planting. Compacted areas are first sub-soiled. The field is ploughed and secondary tillage is used to produce a firm, fine seedbed. Seed can be sown in a conventional manner with a drill, or direct-drilled (no-till) or broadcast. The soil is usually rolled before
and after sowing. In Northern Europe sowing would normally take place in late April or early May at a rate of 400 PLW/m². It is important that weeds do not dominate in the first year and a post planting herbicide may be necessary to ensure this. In the first year no nitrogen should be applied, but phosphorus and potassium should be applied if the soil availability is low. Early indications are that fertilizer applications of 50 kg N are adequate in subsequent years. [98].

Deep soils that have good water holding capacities and adequate drainage are best but switchgrass is adapted to a wide range of soils [28]. Switchgrass tolerates soil with pH values ranging from 3.9-7.6. [92]

Production from seed results in lower establishment costs than SRC or miscanthus, but it yields slightly less than miscanthus. [99]

Switchgrass can be difficult and slow to establish and this can lead to failure of stands. Many factors contribute to these failures but little field based research has been carried out. Of the research that has been conducted, the results are inconclusive or contradictory. In the US, one of the primary objectives of their breeding programmes is to improve establishment capability. Dormancy in switchgrass seed is very complicated and high in neoteric seed. Presowing preparation of the seed may be necessary to achieve good establishment. Seedbed conditions and depth of sowing are other important factors that need to be considered to reduce establishment failures [100].

The majority of production development is based in the US. The US climate can allow a forage crop to be cut twice a year for fodder with the crop being grazed or cut while the crop is still green. The two cut system will require nitrogen fertiliser as the crop is harvested/grazed before remobilisation of the nutrients has occurred thus removing high levels of nitrogen out of the system. Therefore, the nitrogen recommendations for switchgrass are frequently published for a two cut system. In the UK it is very difficult to use the two cut system so the nitrogen requirements in the UK are lower.

Currently, in Europe, switchgrass is harvested in winter/early spring using normal grass bailing equipment. This allows the crop to senesce and remobilisation of the nutrients to the rhizome to occur. This delay in harvesting does result in loses of biomass but will improve the combustion quality of the crop. [94]

Diseases and pests have not been a problem in switchgrass in Europe but crops still require inspection. [28] Sharp Eyespot, *Rhizoctonia cerealis* (observed occasionally in UK field trials) was first identified in a field trial at Rothamsted. Other diseases that occur in the US are Phoma (*Phoma spp.*) (also seen in the UK), rust (*Puccinia spp.*), smuts (*Tilletia maclaganii*), anthracnose (*Colletotrichum graminicola*), leaf spot (*Elsinoë panic*), Helminthosporium spot blotch (*Helminthosporium sativum*), Fusarium root rot (*Fusarium spp.*) and Panicum mosaic virus (PMV). [99]

**13.4.1 Yield**

Optimal productivity can be reached after 2-3 years on light soils and 4-5 years on heavy soils. First year yields are low and may not be economic to harvest. A European project based in the Netherlands found yields of up to 18 tdm/ha in northern Europe. [101] In a UK study, where Switchgrass was established at 9 sites across the UK, the 3rd year yields ranged from 6.02 DM t/ha to 10.02 DM t/ha for the upland ecotype and between 6.89 DM t/ha to 15.36 DM t/ha for the lowland e
yields can be 8-10 tdm/ha and increase further in the third year. The life span of switchgrass is long and in studies at Rothamsted research an approximate yield of 10 t/ha DM has been achieved in two field trials annually for over 10 years (after establishment year).

13.5 Environmental and ecological impacts
Switchgrass is a non-native seeded species and so carries with it some threat of invasion, so must be viewed with some caution. However, experience at Rothamsted has shown that the invasiveness of switchgrass is limited. Any spread of the crop through rhizomes is very small and seed from the crop is only shed over small distances (1-2m). UK native grasses will emerge and grow several months before the switchgrass smothering any emerging switchgrass seed.

Switchgrass provides excellent cover for pheasants, quail and rabbits during autumn and winter; the seeds providing food for pheasants, quail and other birds.

The current research shows that between 0 to 50 kg N/ha/year is adequate for NW European sites while at higher productive sites in southern Europe 50 to 100 kg N/ha/year should be adequate. More specific recommendations for quantity of nutrients cannot be made because this will also depend on the fertility status of the site. [101]

Bullard and Metcalfe carried out a thorough life cycle assessment of switchgrass production [102] and found an energy ratio of 29 and carbon ratio of 41. This included storage in an open-sided barn and a round trip of 40 km to the power plant. Impacts on soil organic carbon levels were also considered in this study and the impact of replacing grassland with switchgrass was found to be neutral; but there were sequestration benefits associated with switching from arable to switchgrass of the order of 182 t/ha.

Samson et al calculated that total production of switchgrass as a pellet required 1.271 Gj/tonne and would give an energy ratio of 1:14.6.[103]

Schumer et al 2008 [104] quoted net energy values of 14.5 MJ-litre\(^{-1}\) ethanol in all sites and harvest years of a US study with the mean NEV 21.5 MJ-litre\(^{-1}\) ethanol.

Nitrogen leaching rates and soil erosion rates are both low compared to arable crops. [102]

13.6 Economics
Preliminary estimates of production cost are 62 euro per tonne in northern Europe. [98] Experience in the UK is that, although switchgrass can be difficult to establish, it is cheap to grow and its profitability competes with Miscanthus. Switchgrass cost between £30-£57/t to produce (1.74 -3.29 £/GJ). This is total costs based on a 20year plantation life and includes a fixed cost of £180/ha/yr [93]
14. Reed Canary Grass

14.1 Feedstock Description
Reed canary grass is a robust, coarse perennial, widely distributed across temperate regions of Europe, frequently in wet places e.g. along river beds. It can grow up to 2m high and flowers in summer, when seed is produced. It has the C3 photosynthetic pathway and is tolerant both of drought conditions and extreme precipitation. It has a high percentage of ash (typically 8%) of which a high proportion is silica. [105]

14.2 Background
It has been extensively used as a catch crop for nutrients in land treatments of waste water and can serve as a substrate for biogas production. [106]
It was identified as having good potential for biomass production in the UK. [93]

14.3 Feedstock Origin
Reed canary grass is widely distributed in temperate to sub tropical regions. It is adapted to wetland habitats but has also been grown successfully on drier soils. It is indegenious to Britain and is commonly found on the verges of rivers and lakes. [107]

14.4 Production
Reed canary grass is produced from seed which is sown in spring early summer at a seed rate of 10kg/ha [107]. In the UK, growth begins early in late winter early spring; it flowers in July after which stems begin to senesce. The crop can be harvested or cut through out the year but for thermal conversion, the crop is usually cut in the winter after the crop has senesced and nutrients have remobilised back to the rhizome. This will reduce the concentration of heavy metals in the crop which lowers the feedstock quality.

Cultivation should prepare a fine seedbed to ensure a good contact between the soil and seed. The seedbed preparation is the same for all of the energy grasses (Switchgrass and Miscanthus). Post sowing rolling is usually required to consolidate the soil and conserve moisture.

Reed canary grass requires some nitrogen fertiliser to increase biomass yields. Previous studies at Rothamsted have show that 100-150 kg N/ha-1 may be required to produce maximum yields (Unpublished).

Reed canary grass does respond to nitrogen and has a relatively high N uptake capacity.

Broad leaf weed herbicides are applied in the establishment year and are occasionally applied in later years if the BLW become a problem. Riche 2005 [93] expressed that although there were concerns with weed control in RCG, few herbicides were necessary in the UK based trial.
Herbicide applications of glyphosate etc. that are applied on Switchgrass and Miscanthus, cannot be applied on RCG. RCG does not go through a complete
dormancy period in early spring and therefore these herbicides cannot be used as they would kill the RCG.

**14.4.1 Yield**
Recorded yields in the UK have been low (4 tdm/ha) but much higher in other northern European countries (10 tdm/ha in Sweden). [105] However, harvest and storage losses, partly caused by the need to delay harvest until the crop is drier, can result in substantially lower figures. [108]

Nixon and Bullard [109], stated that yields in excess of 15 odt ha-1 have been obtained for reed canary grass although in the TOPGRASS study [93] yields across the UK ranged from 2.93 – 8.74 odt/ha.

**14.4.2 Environmental and ecological impacts**
Although Reed canary grass is native to North America the crop European strain of the species is causing problems within the US and Canada. The European strain is more aggressive and there is no reliable method to identify the two strains. The European strain was introduced to the US for forage and erosion control as it had been agronomically improved for increase vigour and drought tolerance. Reed canary grass is an invasive weed in the US and Canada

Reed canary grass is sometimes used in a bed system to remove nutrients from waste water

Reed canary grass has been extensively used as a catch crop for nutrients in land treatment of waste water. [106]

**14.5 Economics**
RCG is cheap and reliable to establish but requires nitrogen fertilizer for full yield potential to be reached and also can suffer from pest attack. Full yield potential appears to be less than miscanthus and switchgrass and therefore costs of production are higher, £43 and £73/t to produce. [93]

**14.6 Environmental and ecological impacts**
Reed canary grass is sometimes used in a bed system to remove nutrients from waste water.
15. Marine Biomass

15.1 Introduction
Marine biomass would appear to have significant potential as an energy source, given the size of the resource: more than three quarters of the surface of planet earth is covered by water [110]. Moreover, of net primary production of biomass, it is generally accepted that 50% is terrestrial and 50% aquatic (ibid). To date, bioenergy policy has largely focussed on the use of land plants, with relatively little consideration of the non-food applications and utility of macro- and microalgae and their products (ibid). Yet, increasing competition for land is driving the current consideration of the potential of the aquatic environment for the production of biofuels and industrial feedstocks (ibid). This review summarises the key issues relating to marine biomass. It draws very heavily on a recent report for the EC EPOBIO program, which in general seeks to realise the economic potential of plant-derived raw materials [110]. The review focuses on marine biomass and its potential energy use only.

15.2 Feedstock description
Carlsson et al [110] state that macro-algae or “seaweeds” are multicellular plants growing in salt or fresh water. They are often fast growing and can reach sizes of up to 60 m in length ([111] in ibid). They are classified into three broad groups based on their pigmentation: i) brown seaweed (Phaeophyceae); ii) red seaweed (Rhodophyceae) and iii) green seaweed (Chlorophyceae). Seaweeds belong to the lower plants, meaning that they do not have roots, stems and leaves, but are instead composed of a thallus (a relatively undifferentiated extension) and sometimes a stem and a foot. Some species have gas-filled structures to provide buoyancy [110]. They are subdivided in three groups, the red, green and brown macroalgae. Currently, seaweeds are mainly utilised for the production of food and the extraction of hydrocolloids [110]. Several species appear to be especially suited for large-scale cultivation (Table 15.1). The website [link] provides details on over 122,000 types of algae.

15.3 Production
15.3.1 Macro-algae
Commercial farming of seaweed has a long history, especially in Asia. The kelp Laminaria japonica is currently the most important, with 4.2 million tonnes cultivated mainly in China [112]. Approximately 200 species of seaweeds are used worldwide, about 10 of which are intensively cultivated, such as the brown algae Laminaria japonica and Undaria pinnatifida, the red algae Porphyra, Eucheuma, Kappaphycus and Gracilaria, and the green algae Monostroma and Enteromorpha [110]. World production of seaweeds was some 8 million tonnes in 2003 [111] in [110]. The USA, Canada and European countries are attempting to establish large-scale seaweed cultivation. [113-115] in [110]
Table 15.1 Suitable macroalgal species for large-scale cultivation (Marine Biomass Workshop, Newport Beach, Florida, 1990; Chynoweth 2002, in [110])

<table>
<thead>
<tr>
<th>Seaweed genus</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Alaria</strong></td>
<td>Possesses floating structure, occurs in arctic waters</td>
</tr>
<tr>
<td><strong>Corallina</strong></td>
<td>Calcareous, spread widely, small, can possibly be grown together with other species</td>
</tr>
<tr>
<td><strong>Cystoseira</strong></td>
<td>Moderate climate zone floating reproduction structures</td>
</tr>
<tr>
<td><strong>Ecklonia</strong></td>
<td>Subtropical and moderate climate zone one floating species</td>
</tr>
<tr>
<td><strong>Egregia</strong></td>
<td>Moderate climate zone floating structure</td>
</tr>
<tr>
<td><strong>Eucheumia</strong></td>
<td>Already cultivated in tropical areas relatively small size</td>
</tr>
<tr>
<td><strong>Gracillaria</strong></td>
<td>Widely occurring often cultivated</td>
</tr>
<tr>
<td><strong>Laminaria</strong></td>
<td>Extensively grown in moderate climate zones</td>
</tr>
<tr>
<td><strong>Macrocystis</strong></td>
<td>In semi culture, seasonal harvest, moderate climate zone</td>
</tr>
<tr>
<td><strong>Pterygophora</strong></td>
<td>Moderate climate zone, very robust species</td>
</tr>
<tr>
<td><strong>Sargassum</strong></td>
<td>Widely occurring (including Sargasso Sea), many species, floating structures, in moderate and tropical climate zones</td>
</tr>
</tbody>
</table>

Carlsson et al [110] summarise American experience in which several types of large-scale cultivation systems were designed and tested for applications in the open sea [116] in ibid. These included free-floating cultivation systems (dynamically positioned by ships) and systems anchored to the seabed or buoys. A typical problem was that anchors were lost, causing the line system to get tangled. In other tests, the structure of the line system remained intact, but the seaweeds were flushed from the lines. This was attributed to the different dynamics of the line system and the seaweeds. Thus, it was recommended to limit movement of the lines by choosing a good geometry or putting the lines under tension. Circular ring structures (15 meter diameter) were also tested, and found to be well suited for the cultivation of **Macrocystis** (kelp) [110]. A Dutch study [115] in [110] investigated the potential of using off-shore wind farm infrastructure, using the experience of the US Marine Biomass Program [116], French [113], and German studies [114]. For floating seaweed species such as **Sargassum** it may be possible to use floating cultivation, and to apply a structure that keeps the seaweed in a limited area. This should lead to significant cost-savings compared to line-based systems [110].

15.3.2 Micro-algae

Carlsson et al [110] provide references relating to the exploitation of micro-algae for bioenergy generation (biodiesel, biomethane, biohydrogen), or combined applications for biofuels production and CO$_2$-mitigation, by which CO$_2$ is captured and sequestered. However, most research and production activity with micro-algae work is for health foods, food supplements, pharmaceuticals and cosmetics (ibid). Production takes place in open ponds, natural lakes, glass tubes, basins, lagoons and photobioreactors; the latter being nutrient-rich tube systems into which sunlight is directed.
15.4 **Economics**

15.4.1 **Biomethane**

The production cost of biomethane from marine algae (even with favourable assumptions) was found to be a factor of 2 – 10 times higher than the cost of natural gas (see Table 15.2 below). High technological and economic uncertainties were associated with the large-scale production of macro-algae in the open ocean [116] in [110]. Nevertheless, it was found that marine algae, such as *Gracilaria sp.* and *Macrocystis* (kelp) were excellent substrates for biomethane generation [117, 118] in [110]. Indeed, Carlsson et al (ibid) state that the view expressed by many authors is that the best approach to biomethane production from macro-algae is the multi purpose use of algal biomass, for example gas production arising from digestion of the residues from hydrocolloid extraction [119, 120] in [110], ibid).

<table>
<thead>
<tr>
<th>Energy crop</th>
<th>Methane cost (US$ per GJ)</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sorghum</td>
<td>6-8</td>
<td>Legrand (1993)</td>
</tr>
<tr>
<td>Poplar</td>
<td>3 – 7</td>
<td>Legrand (1993)</td>
</tr>
<tr>
<td>Kelp</td>
<td>3-14</td>
<td>Bird (1987)</td>
</tr>
</tbody>
</table>

15.4.2 **Micro-algal biodiesel**

Whether or not biodiesel production from micro-algae is commercially viable on a large scale, particularly given the low selling price of biodiesel (less than €1/kg) in 2007 is contested and uncertain [110] highlight a major current problem for the commercial viability of as the low selling price of biodiesel. They cite John Lewnard, Vice President of Process development with GreenFuel Technologies Corporation in 2006, as stating that “productivities of about 100 grams of algae per m² per day are needed to achieve commercial viability” [121] in ibid. This is about three times the level of productivity demonstrated during the Aquatic Species Program funded by the DOE. Similarly cited is Gerald R. Cysewski, president of Cyanotech Corporation: “In the laboratory, you can create some very efficient bioreactors, but it just isn't scalable” [121]. However, Carlsson et al [110] also cite Yustuf Chisti, in a review of biodiesel from microalgae, as stating: “… the level of improvement necessary [in the economics of microalgal biodiesel] appears to be attainable” [122].

15.4.3 **Algal biohydrogen**

Carlsson et al [110] refer to Amos [123] as stating that a 2004 cost analysis seems to indicate that with very optimistic assumptions, cost effective production of hydrogen by algae might be possible. However, the base scenario of Amos (ibid), with an optimistic minimum hydrogen selling price of US$ 13.53/kg, itself makes the highly optimistic assumption that the system investments required would be only US$ 10/m² and assumes a high hydrogen production rate of 300 kg per day (which is higher than demonstrated productivities in laboratory experiments).

Carlsson et al [110] cite the main factors affecting the cost of hydrogen production by micro-algae as:
i) the cost of the huge photobioreactor: for example, an area of about 11 ha was assumed by Amos [123];
ii) the cost of hydrogen storage facilities.

If costs for the photobioreactor could be reduced to US$1/m², and the hydrogen could be transferred to an existing hydrogen pipeline, a minimum hydrogen selling price of US$ 2.83/kg was calculated, which is just above the US DOE cost goal for renewable hydrogen of US$ 2.60/kg [123] in [110].

15.5 Environmental and ecological impacts

Harvesting or farming of marine algae will entail a qualitatively different range of impacts compared to agricultural crops. While there is relatively little literature on the environmental impacts of marine biomass production for energy, there is a substantial body of legislation that marine biomass production and/or harvesting would be subject to in the UK. There is also a larger literature on the systems and impacts of aquaculture and mariculture. Aquaculture is a form of agriculture in which plants and animals are cultures in farms in fresh water bodies. When seawater is used, the practice is called mariculture [124]. The adverse impacts of marine biomass production for energy may show some similarities with those of aquaculture and mariculture, depending on the particular system in use. Near-shore, onshore and fertilised marine biomass production systems may have impacts akin to those of aquaculture and mariculture, but there is also a literature that investigates integrated production systems that are intended to minimise adverse effects while producing a range of marine products.

UK coastal communities have long made use of uprooted kelp along the high tide line, for example, for fuel and fertiliser. However, it is not difficult to imagine that wild harvesting of marine algae on a large scale would have a major impact on marine life, and that there would be harvesting thresholds beyond which the algae resource would not be capable of self-renewing. What is less clear are the potential impacts of UK farmed algae, macro and micro. These could well be positive impacts, depending on the production system: one can imagine marine algae cultivation providing shelter and food for other marine life. The following sections illustrate some of the potential impacts and summarise associated regulation, the latter for the reason that it may be less familiar to the bioenergy community than is terrestrial legislation.

15.5.1 Impacts – aquaculture and mariculture

Aquaculture now provides a third of total fisheries production worldwide [125]. Half of the total aquaculture yield comes from land-based ponds and water-based pens, cages, longlines and stakes in brackish water and marine habitats. However, there have been significant negative environmental and social effects associated with aquaculture and mariculture. The environmental impacts include: mangrove loss, by-catch during collection of wild seed and broodstock, introductions and transfers of species, spread of parasites and diseases, misuse of chemicals, and release of wastes. The socioeconomic impacts include: privatization of public lands and waterways, loss of fisheries livelihoods, food insecurity, and urban migration (ibid). Although commenting from a Philippines perspective, Primavera’s account of the range of issues to consider will be generally applicable to UK ecosystems: relevant recommendations include combining herbivorous and omnivorous species; self-regulation in the form of codes of conduct and best management practices; regulations
based on holistic Integrated Coastal Zone Management based on stakeholder needs; the establishment of mechanisms for conflict resolution; the need to account for the limited assimilative capacity of the environment; protection of community resources; rehabilitation of degraded habitats; management of feed, water, and effluents (ibid).

Troell et al [126] agree that reducing negative environmental impacts from aquaculture activities is a key issue for ensuring long-term sustainability of the industry. They examined the major findings and methods of 28 peer-reviewed studies on marine aquaculture systems that integrated fed and extractive organisms (those that remove particulate organic nutrients), including seaweeds. Troell et al [126] identified 10 research recommendations, including investigations of social acceptability. Troell et al (ibid) state that polyculture has a long history in the freshwater environment, but not in marine and brackish waters. They state that though poorly studied in the past, a renewed interest in integrated techniques emerged in the early 1990s, and several different systems have since been proposed. These have attempted to: reduce the negative impacts of fed aquaculture on the aquatic environment; to productively remove and recycle toxic metabolites by using recirculating systems; to increase production of specific co-cultured extractive species (e.g. shellfish and seaweeds); and to increase overall productivity of the resources of feed, water and fossil energy (ibid). It should be noted that none of the studies examined by Troell et al (ibid) involved the cultivation of seaweed alone.

Buschmann et al [127] review the environmental effects and alternative production strategies of marine aquaculture in Chile. The study is unusual in including a separate discussion of the impacts of seaweed cultivation. They found that seaweed cultivation can have an impact on sedimentation processes, increase of invertebrate assemblages and algal epiphytic abundances. At the time of the study, Chile was producing over 48,000 tonnes of the farmed agarophytic red alga *Gracilaria*. Buschmann et al (ibid) discuss the methodological aspects of inferring impact –finding an equivalent comparison site is not as straightforward as might be imagined. They state that a consideration of the spatial and temporal environmental heterogeneity is crucial for the successful implementation of adequate sampling designs (ibid: 401). They also advocate baseline monitoring, i.e. prior to any impact.

The seaweed farming areas considered by Buschmann et al [127] were licensed by the state to local artisanal farmers or to larger companies and their size varied between less than 1 ha to 80 ha or more. In fact the availability of suitable cultivation areas had become a limiting factor. In terms of impacts, one problem concerned a popular technique for anchoring the algae to the substratum - the use of sand filled plastic tubes. As replanting is necessary to maintain a high level of production, a problem arose in farms planted with sand-filled plastic tubes. The plastic was more resistant than expected and, as a result of farmers introducing the plastic tubes for a second or a third time for replanting purposes, they remained uncovered by the sand and the algae were eventually lost, without the recovery of the bed [128]. There may have been other effects such as modifications in the sediment and in fauna composition.

Other problems described by Buschmann et al [127] include the massive [sic] expansion in numbers of organisms such as algal epiphytes, herbivore gastropods, polychaetes (bristle worms) and fishes, as well as mussels competing with the algae for space. The experimental use of agrochemicals (pyretroids) to control these organisms has shown that they can kill many species of invertebrates, in particular the
most important benthic predator in this area, the crab, *Hemigrapsus canaliculatus* (ibid). However, this would disturb the stability of predator-prey interactions (ibid).

Buschmann et al [127] state that another documented environmental effect associated with *Gracilaria* cultivation is the increased sedimentation found in some subtidal cultivation systems [129, 130]. It appears that this is a result of *Gradaria* acting as a sediment trap (ibid). Nevertheless, Buschmann et al [127] stated that the effects of variations in the sediment on fauna composition and abundance are unknown and require further study. Buschmann et al [127] also state that while macroalgae from other geographical areas had not yet been introduced into Chile for commercial purposes, *Gracilaria chilensis* had been transported to different regions of the Chilean coastline and that the epiphytes and endophytes present in commercial beds of *Gracilaria* (e.g. [131-133] or *Iridaea* [134] can also be transported and this aspect required further attention.

Olafsson et al [135] reported on a study of open water aquaculture of the seaweed *Eucheuma spinosum*, imported to Zanzibar from the Philippines in 1989. The aquaculture was a large scale operation on the island, with algal farms covering around a 1000 ha of the intertidal area. To assess the effects of the farming on benthic communities both field and laboratory studies were conducted. Two field studies conducted at different times showed that all major meiofaunal\(^2\) taxa were found in significantly lower numbers within the farm area compared with control areas. Specifically, the trophic structure of the nematode assemblage was characterised by a high number of epistrate feeders in all areas ranging from 73 to 96% of total numbers in the samples. To test the hypothesis that toxic substances excreted by the seaweed were responsible for lower abundance inside the farm area, a laboratory experiment was conducted. *Eucheuma* plants were added to several microcosms and allowed to grow there for 40 days. The results indicated no effects of the seaweed on the density of the major infauna taxa. It was concluded that other factors such as increased predation by benthic feeding fish and the mechanical disturbance of the sediments may better explain the observed differences in infauna abundance inside and outside the algal culture farms.

Neori et al [136] are among many who advocate integrated forms of aquaculture, in which seaweed is used for biofiltration purposes. Rising global demand for seafood and declining catches have resulted in the volume of mariculture doubling each decade, a growth expected by the FAO to persist in the decades to come (ibid). Feed accounts for about half the cost in current, high-volume fed mono-species aquaculture, mainly fish net pens or shrimp/fish ponds, yet most of this feed becomes waste (ibid).

As in traditional polyculture systems, plants can drastically reduce feed use and environmental impact, while at the same time increasing income generation (ibid). Nutrient-assimilating, photoautotrophic plants use solar energy to turn nutrient-rich effluents into profitable resources. The plants counteract the environmental effects of the heterotrophic fed fish and shrimp and restore water. Integrated intensive aquaculture approaches, developed from traditional extensive polyculture, integrate the culture of fish or shrimp with vegetables, microalgae, shellfish and/or seaweeds (ibid). Integrated mariculture can take place in coastal waters or in ponds using

\(^2\) “animals ranging in size from approximately 0.1 mm to 1 mm that live within the sediments, the size class of transition from micro- to macrofauna” (Biology online: [http://www.biology-online.org/dictionary/Meiofauna](http://www.biology-online.org/dictionary/Meiofauna)).
generic, modular and adaptable technologies for several culture combinations of fish, shrimp, shellfish, abalone, sea urchin and several species of commercially important seaweeds and vegetables. A 1-ha land-based integrated seabream–shellfish–seaweed farm can produce 25 tons of fish, 50 tons of bivalves and 30 tons fresh weight of seaweeds annually. Another farm model can produce in 1 ha 55 tons of seabream or 92 tons of salmon, with 385 or 500 fresh weight of seaweed, respectively, without pollution (ibid). Preliminary calculations show a potential for high profitability with large integrated farms. Neori et al (ibid) conclude that, modern integrated systems in general, and seaweed-based systems in particular, are bound to play a major role in the sustainable expansion of world aquaculture

15.5.2 Regulatory framework
In the context of the USA and marine biotechnology, but of wider relevance, Knecht et al [137] state that: “there are no coherent guidelines, framework conventions, guiding norms or principles to specifically govern the conduct of marine biotechnology development neither in the United States nor in other countries. A number of existing international agreements related to maritime jurisdictions, protection of biodiversity, and intellectual property, however, will significantly affect the operations of the U.S. marine biotechnology industry both in the U.S. and in the jurisdictions of other nations”.

15.5.2.1 International
Marine biomass cultivation is – in principle - subject to regulation at different levels. At the international level, the United Nations Convention on Law of the Sea (UNCLOS) defines the rights and responsibilities of nations in their use of the seas, establishes clear guidelines for businesses, protects the environment and improves the management of marine natural resources (Carlsson et al, ibid). The Convention was concluded in 1984 and came into force in 1994. To date, 154 countries and the European Community have joined the Convention; the United States has not (ibid). Under UNCLOS, States have the obligation to protect and preserve the marine environment, but also have the right to exploit their natural resources pursuant to their environmental policies and in accordance with their duty to protect and preserve the marine environment. States must prevent, reduce and control pollution, including that resulting from the introduction of species to a particular part of the marine environment (ibid).

15.5.2.2 European
At the European Community level, Owen and Chambers [138] review the relevant aspects of environmental legislation, all of which is applicable and interpreted at the UK level.
**Habitats Directive**

The aim of the Habitats Directive is “to contribute towards ensuring biodiversity through the conservation of natural habitats and of wild fauna and flora…” (Art 2(1) HD). Measures taken pursuant to the Habitats Directive are to be designed “to maintain or restore, at favourable conservation status, natural habitats and species of wild fauna and flora of Community interest” (Art 2(2) HD; see also Art 1(b), (c), (e), (g) & (i)) and are to “take account of economic, social and cultural requirements and regional and local characteristics” (Art 2(3) HD) [138].

Lloyd-Evans [139] and Owen and Chambers [138] point out that as a result of a legal case in 1999 brought by Greenpeace against the UK Government, the EU Birds and Habitats Directives were required to be extended to cover the entire ‘200 mile limit’ and not just the UK’s territorial waters, as the government had previously interpreted them. Consequently, the identification and selection of marine Special Areas of Conservation (SACs) and Special Protection Areas (SPAs) was required, as part of the Offshore Natura Project (ibid). Lloyd-Evans continues: “Without investment in making the move from wild harvesting to managed exploitation in a clear and consistent way, there will be a severe brake on the exploration and utilisation of marine resources of any sort”.

**Birds Directive**

Owen and Chambers [138] state that the Birds Directive “relates to the conservation of all species of naturally occurring birds in the wild state in the European territory of the Member States to which the Treaty [establishing the EC] applies” (Art 1(1) BD). In general, Member States are to take “the requisite measures to maintain the population of the species referred to in Article 1 at a level which corresponds in particular to ecological, scientific and cultural requirements, while taking account of economic and recreational requirements, or to adapt the populations of these species to that level” (Art 2 BD). Annex I includes several marine and coastal bird species and the term “regularly occurring migratory species” additionally encompasses many other marine and coastal species not listed in Annex I [138].

**EIA Directive**

Owen and Chambers [138] state that the EIA Directive – i.e. Directive 85/337/EEC as amended by Directive 97/11/EC and Directive 2003/35/EC - applies “to the assessment of the environmental effects of those public and private projects which are likely to have significant effects on the environment” (Art 1(1) ED). Art 2(1) ED states that: Member States shall adopt all measures necessary to ensure that, before consent is given, projects likely to have significant effects on the environment by virtue, *inter alia*, of their nature, size or location are made subject to a requirement for development consent and an assessment with regard to their effects. Owen and Chambers (2004) are of the view that bio-prospecting is unlikely to be subject to EIA, which seems fair, but a large scale extraction of marine biomass very likely would be subject to EIA due to the ‘significant’ effects of this.

**SEA Directive**

Owen and Chambers [138] state that the objective of the SEA Directive is “to provide for a high level of protection of the environment and to contribute to the integration of environmental considerations into the preparation and adoption of plans and
programmes with a view to promoting sustainable development, by ensuring that, in accordance with this Directive, an environmental assessment is carried out of certain plans and programmes which are likely to have significant effects on the environment” (Art 1 SD). Art 3(1) SD requires Member States to carry out an environmental assessment for “plans and programmes referred to in paragraphs 2 to 4 [of Art 3 SD] which are likely to have significant environmental effects” [138]. A plan or programme of marine biomass cultivation or harvesting arguably should require an SEA.

**EC Thematic Strategies**

Carlsson et al (ibid) state that the current regulatory framework under development (Proposals for a Framework for Community Action in the field of Marine Environment Policy 16976/06) notes that policy should provide a basis for a strong, growing and competitive maritime economy in harmony with the marine environment. The aim is that marine environmental policy ensures that the use of the marine environment is at a level that is sustainable with marine species and habitats protected, human induced decline of biodiversity prevented and diverse biological components allowed to function in balance. Beyond this, Carlsson et al [110] state that there is little in current EU policy proposals that addresses issues relevant to the production and utilisation of marine biomass (ibid). However, COM(2006) 275 final, the Commission’s Green Paper entitled “Towards a future Maritime Policy for the Union: A European vision for the oceans and seas”, “aims to launch a debate about a future Maritime Policy for the EU that treats the oceans and seas in a holistic way” (ibid:4).

Lloyd-Evans [139] observes that the European Commission’s white paper on a strategy for the marine environment - COM(2002) 539 final - may be a brake on bioprospecting and on applications of marine biotechnology or may encourage cautious and well-controlled development. The white paper proposes objectives and actions to rationalise existing legislation and marine conventions that are in some cases are confusing or duplicative (ibid). Relevant overarching objectives are to halt biodiversity decline by 2010, ensure a sustainable use of biodiversity and approach concentrations of hazardous substances that are near background for naturally-occurring and almost zero for man-made synthetic compounds (ibid).

With regard to land-based systems for the production of aquatic biomass, in Europe there are controls in respect of discharges from land-based facilities and Directive 91/271/EEC concerns the collection, treatment and discharge of urban waste water and the treatment and discharge of waste water from certain industrial sectors. Industrial waste water entering collecting systems and the disposal of waste water and sludge from urban waste water treatment plants are both subject to regulations and/or specific authorisations on the part of the Member States’ competent authorities (ibid).

**15.6 Social context**

Carlsson et al [110] outline the regulatory framework of marine biomass production as below. They do not discuss public and stakeholder perceptions per se, however. These are likely to prove significant, particularly with respect to onshore and coastal developments. For example, a study into the prospects for marine biotechnology development in the UK [139] identifies as a challenge the “conflict between the perceptions of sea as nature and genetic enhancement techniques as the opposite, suggesting a careful choice of ‘flagship’ products and a strong, coherent sector
branding”. It should be noted that Lloyd-Evans (ibid: 19) does not include energy supply as an area in which the UK could “become a major force in the use of marine biotechnology”. In fact Lloyd-Evans devotes only some five lines to a discussion of the energetic potential of UK marine biomass, perhaps because the report has a genetic modification and molecular level focus.

Seaweed harvesting can be hazardous and arduous and methods will differ nationally according to available technologies, levels of development and capital availability. Reuters [140] report the case of a Chinese seaweed farmer being jailed for five years and six months for his role in the drowning of 19 people, including his own wife, who were swept away by a rising tide. This is not to say that such events are country-specific: the same report refers to the 2004 incident of 30 Chinese cocklers being caught by tides in Morecambe Bay, England, of which 18 died.

15.7 Prospects/status

15.7.1 Biomethane

Carlsson et al [110] report that research to determine the technical and economic feasibility of bio-methane production from marine biomass was conducted from 1968 until 1990 under the sponsorship of the U.S. Navy, the American Gas Association and Gas Research Institute, and the U.S. Department of Energy, and has been reviewed by Chynoweth [116]. The latter study compared the technical energy potential of marine algae, wood and grass species and municipal solid waste and concluded that marine biomass offered the highest potential. Chynoweth (ibid) concluded that farming of macro-algae near shore with nutrient supply supplied through recycling of wastes from conversion processes would be a better option for ensuring adequate nutrition than attempting to induce deep-ocean upwelling.

15.7.2 Bio-oil

Pyrolysis and thermochemical liquefaction can both produce a bio-oil from biomass. In both processes, biomass is heated in the absence of oxygen and at high temperature and is converted into products that include char, oil and gas. Pyrolysis requires drying of the biomass, while in thermochemical liquefaction, wet biomass is treated at a somewhat lower temperature and high pressure. A biomass to liquids process capable of using wet material such as algal biomass has a clear potential advantage over pyrolysis [110] ibid.

Carlsson et al (ibid) report that the production of liquid fuel or bio-oil via pyrolysis or thermochemical liquefaction of micro-algae has been demonstrated for a range of micro-algae [141-147] all in [110] ibid. Carlsson et al (ibid) describe example studies in further detail: Ginzburg [148] ] reported that a mixture of hydrocarbons was formed upon pyrolysis of suspensions of the micro-algae Dunaliella sp. Miao et al. [149] proposed using micro-algae harvested from lakes both to produce bio-oil via fast pyrolysis and as an environmental solution to reduce algae blooms. They found that up to 24% of the dry biomass was recovered as bio-oil. The pyrolysis oils had better properties than the oil from lignocelluloses, but still had a much higher oxygen content compared to fossil oil and their heating value was low, with 29 MJ/kg.

3 Photographs of Chinese seaweed harvesting can be viewed here: http://www.azote.se/index.asp?str=Nils%20Kautsky&lb=&sa=0&b=1
compared to 42 MJ/kg of fossil oil [149]. Miao et al. [149] also investigated fast pyrolysis of micro-algae in the laboratory (ibid, in [110]).

Carlsson et al [110] report that in a further study, Miao and Wu [149] produced a bio-oil with improved properties via fast pyrolysis of heterotrophically grown Chlorella protothecoides. The heterotrophically grown algae (i.e. requiring complex organic molecules) had a higher lipid content (some 55%) compared to autotrophically grown algae (some 14%). The heating value of 41 MJ/kg was nearly as high as that of fossil oil, and the nitrogen content was reduced to about 1%. This bio-oil still had a relatively high oxygen content of some 11% compared to fossil oil with 0.05 to 1.5%. Key to improving the bio-oil quality was the increase in lipid content, which can be achieved by growing the algae heterotrophically under laboratory conditions or in closed systems. In contrast, algae harvested from lakes may not contain a high concentration of lipids (ibid).

15.7.3 Biodiesel
Carlsson et al [110] report that in an NREL project, Sheehan et al. [150] collected some 3,000 strains of algae from the northwest and the south-eastern regions of the continental U.S. and Hawaii, and screened them for their oil-producing capacity. Many species of algae accumulate large amounts of oils that to a large extent are made up of triacylglycerols consisting of three fatty acids bound to glycerol. The fatty acids are saturated or unsaturated carbon chains of different lengths. Non- or mono-unsaturated fatty acids of 16 or 18 carbon length are preferable sources to use for the production of biodiesel.

Relevant here is the fact that very long chain polyunsaturated fatty acids (vlcPUFAs) are less suitable for the production of biodiesel, as polyunsaturation leads to increased oxidation problems in the fuel. However, the unsaturation of algal oil can be reduced by making use of the commonly used technology of partial catalytic hydrogenation of the oil (Dijkstra 2006; Jang et al. 2005), the same technique that is used in making hydrogenated margarine from vegetable oils [110]. Algal oil is converted into biodiesel through a trans-esterification process. That is, the oil extracted from the algae is mixed with alcohol and an acid or a base to produce the fatty acid methylesters that make up the biodiesel ([122] in [110]).

15.7.4 Algal biohydrogen
The advantages of hydrogen include its capacity to combust to water, abundant feedstocks (water, biomass or hydrocarbons) and non-toxicity. However, it is difficult to store and transport; it has a propensity to make steel brittle, would leak from natural gas pipelines in high concentration, and is expensive to compress (after [110]).

Hydrogen can be produced by algae under specific conditions and for overviews of the prospects of hydrogen production by algae, Carlsson et al (ibid) refer to Levin et al. [151]; Prince and Kheshgi [152]; Rupprecht et al. [153] and Hankamer et al [154]. Carlsson et al (ibid) identify three different ways to produce hydrogen from algae: direct and indirect photolysis (breaking down of the algae via the action of light), and ATP-driven H₂-production (ATP is Adenosine 5’-triphosphate, a nucleotide that acts as an energy carrier within cells, for metabolism). Direct photolysis is possible when photosynthesis and water-splitting are coupled, resulting in the simultaneous production of hydrogen and oxygen. These must be removed from the process, entails
a major safety risk, and has cost implications. Moreover, the hydrogenases involved in
the processes are extremely oxygen-sensitive (hydrogenases are enzymes that catalyse
the reversible oxidation of hydrogen; they are important in anaerobic metabolism)
Carlsson et al (ibid).

For these reasons, indirect processes of hydrogen production are likely to be
preferred. In these processes, cells accumulate a carbon storage material such as
starch, the energy-content of which is partially converted to hydrogen under anaerobic
and sulphur-limited conditions. Carlsson et al (ibid) state that the process still remains
to be convincingly demonstrated.

15.7.5 Conclusions
There is relatively little literature directly relevant to UK use of marine biomass for
energy. There is, however, a body of literature providing an indication of relevant
regulation, applications and impacts. UK marine biomass cultivation would need to be
strictly regulated and for cost and logistical reasons is more likely to be inshore than
in deep water. Energy uses would be in competition with uses that are probably more
economically valuable: pharmaceuticals, cosmetics, food supplements and so on.
Although the UK has an extensive shoreline, as an island, it is difficult to imagine
marine biomass contributing substantially to UK energy needs. That said, this view is
not based on any quantitative estimates and may be overly conservative. In the short
to medium term at least, Carlsson et al [110] judge that the most likely energy-related
use of macro-algae may be for biomethane as part of multi purpose use: for example
gas production arising from the digestion of the residues from hydrocolloid extraction
for agar and alginates, for the food and pharmaceutical industries.
16. Oil seed rape

16.1 Feedstock description

Oil seed rape (or Canola) is a brassica, a genus of plants in the mustard family (Brassicaceae), which includes cabbages, some root vegetables and many seeds, including mustard and oil seed.

There are two rapeseed species (B. napus and B. campestris) both of which have spring and winter annual forms. The winter forms are more productive than the spring forms but are generally less winter hardy than winter cereals.

Brassicas can germinate and grow at low temperatures (T\text{Base} = 1°C) so can be cultivated in cooler agricultural regions and at high elevations. Major producing regions include China, the Indian subcontinent, Canada and Northern Europe.[155]

The small, round brassica oilseeds normally yield on extraction over 40% oil on a dry weight basis and a meal containing 38 to 44% high quality protein. About 80% of the monetary value of the seed is derived from the extracted oil, the residual high protein meal contributing the remainder.

Unlike grain or corn, rapeseed cannot be grown in monoculture, and it is advisable to cultivate Canola on the same field only every third or fourth year for both economic and agronomic reasons. Therefore potential rapeseed cultivation on available farm land is limited. [156]

16.2 Feedstock origin

In Europe domestication of the plant occurred in the early middle ages and commercial plantings of rapeseed were recorded in the Netherlands in the 16th century, used primarily as a lamp oil and lubricant.

Over 13.2% of the world’s edible oil supply now comes form the oilseed Brassicas, rapeseed and mustard. Production and usage of brassica seed oils has grown faster in the period 1975-85 than any other oil crop, except the oil palm, making it the third most important edible oil source after soybean and palm.

Despite attracting farmer interest as a “break crop” in cereal based crop rotations prior to 1973, relatively little oil seed rape was grown in the UK until entering the EEC, which was supporting farm prices of oil seeds, owing to a world protein shortage, largely for animal feed. The financial support offered by the EEC and suitability as a break crop on cereal farms made it attractive for UK growers and the area cultivated increased substantially from only a few thousand hectares to more than 100,000 hectares. Despite some moderation of the support mechanism in 1981/2 the market price continued to rise throughout the 1980’s with a tripling of production. [157]

When the EU payment scheme changed in 1991 prices per tonne fell sharply; but the area payments then being made by the EU allowed average return to growers to remain stable. In 1993 the wider Common Agricultural Policy reform combined cereal, oilseed and protein crops under the arable payments scheme; but an agreement with the US also limited the area of oilseeds. The 2000 reform of CAP led to a cut in subsidies, with the higher differential for oilseeds compared to cereals being eroded at the same time as a fall in market price. This caused a reduction in cultivated area; but
improving prices for rapeseed compared to cereals since then have favoured a recovery in oilseed growth. [157]

UK oilseed area has fluctuated closely in line with market prices and policy considerations between 400,000 and 500,000 hectares from 1993 to 2003.[157]

Currently the UK has around 600,000 ha of oilseed rape, but this is mainly used for food products and current biodiesel production of 600 t per month is from used cooking oil and estimates by Rothamstead of about 50,000 ha in 2006, mostly on set aside land. The NFU have estimated that 1.2 billion litres of bioethanol and 1.35 billion litres of biodiesel will be required to meet the 2010 biofuel target in the UK. The biodiesel target would require 2.7 million tones of oilseed rape – an extra 840,000 ha of oilseed rape (assuming that none of the existing 600,000 ha is diverted into fuel). One of the main constraints on growth in the UK is the OSR crush capacity.

16.3 Environmental and ecological impacts

16.3.1 Crop origin and growth pattern

If rapeseed oil were used as feedstock for biofuels in the UK it is likely that a significant proportion of the raw material requirement would be sourced in the UK, as there is already a substantial industry for rapeseed oil production and it is a crop that is suited to the UK climate.

The environmental impacts of increased OSR production in the UK would depend on what the OSR was replacing. The main possibilities are that:

1. existing OSR produced for food would, instead, be used for biodiesel
2. OSR would be grown on current set-aside land
3. OSR would replace other break crops, such as legumes
4. OSR would replace cereal crops.

It can reasonably be assumed that option 1 would be the first recourse and going down the list represents increasingly radical shifts in the current agricultural pattern, which would only be likely to be driven by a shortage of supply which increased market prices substantially.

Attempts have been made to assess the impact of each of these options on greenhouse gas levels, biodiversity, agrochemical use and water courses below.

16.3.2 Energy balance and greenhouse gas impact

In terms of overall greenhouse gas balance for crop production nitrogen fertiliser inputs are one of the most significant elements. Oilseed rape is a nitrogen-demanding crop relative to most other crops (excluding winter wheat) in the arable rotation, but less so for phosphorus and potassium. Between 1998 and 2002 mean nitrogen usage of winter oilseed rape was 194 kg/ha compared to averages for arable tillage crops of around 145 kg/ha.

Work by Mortimer & Elsayed (Date) shows the following estimates of direct and indirect total energy inputs expended in crop production:

Wheat: 19171 MJ/ha
Oilseed rape: 12689 MJ/ha
Sugar beet 17809 MJ/ha
Elsayed et al. (Date) have also calculated total greenhouse gas emission arising from production of a unit area of oilseed rape, wheat and sugar beet (these data should be treated with caution as the role of Nitrous Oxides and to a lesser extent Methane from land has not been fully evaluated):  

Oilseed rape: 1731 kg CO2 eq/ha  
Winter wheat: 2220 kg CO2 eq/ha  
Sugar beet: 627 kg CO2 eq/ha  

1. If existing OSR for food was used instead for biodiesel there would be relatively little impact on energy balance. If the growers seek to save energy inputs by minimising cultivations there would be knock on effects on GHG emissions as nitrous oxide losses are increased.  
2. If natural regeneration set-aside was replaced with OSR for biodiesel production the physical inputs of pesticides, fertilisers and energy utilisation would be increased. The impact of adding nitrogen fertiliser where previously none was applied would be anticipated to have a large effect on nitrous oxide emissions from the land. Should the land have been in set-aside since it’s inception in 1987 there could be some carbon losses in addition.  
3. If other break crops, such as legumes were replaced with OSR there would be an increase in fertiliser nitrogen inputs, which would increase indirect energy use and overall greenhouse-gas emissions.  
4. If oilseed rape replaced cereal crops this would likely result in a small increase in greenhouse gas emissions; but replacing winter wheat would result in a significant reduction in overall greenhouse gas emissions.  

16.3.3 Impact on habitat and biodiversity  
1. Option 1 would have no impact on habitat and biodiversity.  
2. With replacement of set-aside (option 2) farmland habitat diversity (habitat, weed and invertebrate) would be reduced, which would have a detrimental impact on some farmland birds, but other birds of particular concern would benefit.  
3. With replacing other break crops the main impacts on biodiversity would include loss of relatively open canopy crops in the farmed landscape, favoured by birds such as lapwings and skylarks and used for foraging activity by many other species. Where break-crops are spring-sown there are benefits for overwintering birds form cereal stubbles left after harvest of the previous crop, which would be lost with winter OSR (the most common in the UK).  
4. If cereal crops were replaced the effects could be positive as winter oilseed rape is a more bio-diverse crop than winter cereals. In particular the rape crop supports a diverse invertebrate community. Conversely biodiversity impacts could greater should the cereals be grown in combination with measures such as use of unsprayed crop margins or use of in-field fallow patches, environmental measures not appropriate to the rape crop.  

16.3.4 Risks associated with agrochemical use  
On a use per unit area basis, winter wheat and barley crops typically represent moderate use of pesticide inputs, comparable to in puts to sugar beet. In contrast, oilseed rape is a relatively low to moderate user of pesticides.
Attempts have been made to try to generate indices of risks associated with pesticide use across crops and rotations. They are affected by a number of problems but currently represent one of the best means of readily evaluating the risks associated with pesticide application regimes. Recent work showed that the highest impacts arising from pesticide use were likely to arise from potato cropping (index score 230), while sugar beet and winter wheat had similar scores (26 and 35) respectively. Oil seed rape and pea crops were assessed as having intermediate scores (85 and 75 respectively)

1. Option 1 has no impact on agrochemical use
2. If natural regeneration set-aside was replaced with OSR for biodiesel production the physical inputs of pesticides, fertilisers and energy utilisation would be increased, increasing the risks associated with use of these agrochemicals
3. Pesticide inputs would be unaffected by switching other break crops (particularly peas or beans) to oil seed rape.
4. Replacing cereal crops, such as winter wheat with oil seed rape would increase pesticide use and the associated risks.

16.3.5 Impact on water courses – fertiliser and nitrates
There is typically a low level of risk of nitrate leaching from well-fertilised cereal crops while oilseeds represent a relatively high risk of leaching loss, largely as a result of high levels of residual fertiliser left in soil after harvest. None of the pesticides which cause pollution in surface waters are approved for use on oilseed rape.

1. Option 1 may slightly reduce the propensity to leaching if reduced tillage were adopted.
2. Option 2 would increase the risk of nitrate leaching
3. If break crops such as legumes were replaced with OSR there would be a slightly increased risk of nitrate leaching as a result of the greater proportion of residual inorganic N forms following oilseed rape crops.
4. Replacing cereal crops with oilseed rape significantly increases the risk of leaching loss.

16.3.6 Impacts on soil
1. Option 1 has little impact on the soil characteristics, other than the possibility of reduced tillage
2. If natural regeneration set-aside was replaced with OSR for biodiesel production here is possibly a small increase in risks of soil erosion and phosphate loss,
3. Replacing other break crops (such as legumes) would not alter the risk of soil erosion.
4. Replacing winter cereal crops would have little impact as the overall risk of soil erosion is relatively small in winter cereal and oilseed crops compared to that observed with root crops and maize.

16.3.7 Byproduct impacts
Increased use of OSR for biofuels would results in significant increases in quantities of rapeseed meal (RSM) in the UK. If this became available for compound animal
feed (rather than, for example, being consumed in power generation) it could impact on the market price. Depending which protein source it displaced the total protein and amino acid profiles of animal feed rations could alter, potentially increasing the amounts of nitrogen and phosphorus excreted by livestock [158]

16.4 Production

16.5.1 Objectives
Oil content is a vital consideration in the production of rape seed. Most crushers in the UK pay an oil premium of 1.5% for every 1% oil content above 40% with a similar payment deduction below 40%. Oil content is generally defined as %oil in seeds at 9% moisture.

16.4.2 Yield
Commercial yields of oilseed rape has shown little increase from 1980 onwards, with an adjusted yield of around 3-3.5 t/ha. About 25% of oilseed rape cultivated is spring oilseed rape, which has a lower yield of around 2 t/ha. Disease (mainly light leaf spot) can have a major impact on crops so control by fungicide is particularly important. Sulphur deposition from the atmosphere has declined rapidly since the 1980’s and 70% of the UK is estimated to be at high to medium risk from sulphur deficiency, although only 25% of rapeseed area is treated with sulphur. [157]

16.4.3 Agrochemical applications

16.4.3.1 Fertiliser
Current fertiliser recommendations for winter crops in England and Wales are 120-250 kg/ha for mineral soils with Soil Nitrogen Status (SNS) index of between 3 and 9. Of this, 30 kg/ha is recommended for the seebed on soils with and SNS index of 0-10. The large majority of crops from 1999 to 2002 received nitrogen within this recommended range; the average being around 193 kg/ha. [157]

Applying additional spring nitrogen increases seed yield, but decreased its oil content. The optimum appears to be around 190 kg/ha dose of spring nitrogen, which is included in the sulphur dosing below.

P and K requirements vary substantially with soil characteristics. One estimate is [157] 90 kg/ha P and 70 kg/ha K when straw is removed from soil.

16.4.3.2 Sulphur
Oilseed rape has a relatively high demand for sulphur, requiring approximately 16 kg S to produce one tonne of seed at 91% dry matter. Where sulphur is applied oilseed rape receives around 25 kg S/ha.

Applying 30 kg/ha sulphur benefited oil yield. Applying 30 kg/ha S and 190 kg/ha N can be achieved with a first fertiliser dose in February of 30 kg/ha S and 90 kg/ha N (ammonium sulphate with additional ammonium nitrate to give correct total amount of nitrogen), followed by a second dose of N of 100 kg/ha (ammonium nitrate) in either March or April.
16.4.3.3 Glyphosate
Pre-harvest swathing generally results in lower harvested yields than pre-harvest
dessication with glyphosate.

16.4.3.4 Herbicides
Nearly all oilseed rape is treated with herbicides (on average 2.7 times/year), 88% is
treated with fungicides (on average 1.8 times/year) and 80% with insecticides (on
average 1.5 times/year). Herbicide use accounts for 35%, fungicide 25% and
insecticide 17% of the pesticide treated area. [159]
The majority of herbicides are applied to winter oilseed rape between July and
November (as pre-emergence and early post-emergence split treatments, or for grass
weed control) with a smaller peak around March, mostly to rectify and poor
performance associated with earlier weed control programmes. Herbicides are also
commonly applied pre-harvest to even maturity and desiccate the crop as an aid to
harvesting. Glyphosate is most commonly used at or near three-quarters of the full
label rate.

16.4.3.5 Insecticides
For oilseed rape, the majority of insecticides, including cypermethrin, are applied in
autumn, with further applications being made in March.

16.4.3.6 Fungicides
The majority of fungicides are applied to winter oilseed rape between October and
November and/or March for general disease control, particularly for control of
damaging light leaf spot and phoma disease. Further applications in May are
occasionally required for control of steam canker and sclerotinia. Most fungicides
tend to be applied to oilseed rape at, or just above, half the full label rate.
Fungicide applications in the autumn or spring that give significant increase in seed
yield are also likely to maintain or increase oil content and should benefit oil yield and
output value. Applying an autumn fungicide significantly increased oil yields, but
subsequent spring fungicides were of little additional benefit.[160]

16.4.4 Proposed agronomic regime for modelling purposes.
- ploughing
- discing
- power harrowing
- sowing, with insecticide and fungicide applied on seed (small dose, well
targeted)
- rolling
- fertiliser application 1 – February - 30 kg/ha S and 90 kg/ha N (ammonium
  sulphate with additional ammonium nitrate to give correct toal amount of
  nitrogen)
- fertiliser application 2 – March/April 100 kg/ha (ammonium nitrate)
- herbicide application – pre-emergence in Sep, post-emergence in Nov, –
- insecticide application – cypermethrin in Autumn & March
- fungicide – November & March
• dessication – glyphosate at half recommended rate
• combining & carting
• grain drying

16.5 Economics

Biodiesel imports to the EU are subject to an import duty of 6.5%. However, since the EU is currently the principle producer and user of biodiesel in the world, there is little international trade in biodiesel at present.

The increasing global demand for biofuels will result in increased demand for the raw feedstocks, including rape seed oil. This is likely to cause UK cereal prices to rise and will in turn will result in an increase in livestock feed prices. This effect has already been observed in the UK, and the trend is likely to continue. Increases in rape seed oil production would result in additional quantities of rape seed meal being produced. It is possible that the livestock industry could absorb additional RSM produced via biofuel production, displacing other feed materials currently imported into the UK, [158] but with UK livestock numbers falling and other competing materials the likelihood of this is decreasing.

16.6 Social context

There is increasing concern that increased cereal prices could price low-income consumers out of the market for staple foods.[158]

16.7 Status and prospects

In the UK in 2005/06 500,000 ha of oilseed rape was grown on non-set-aside land producing 1674 kt of oilseed rape and 196 kt from 75,000 ha of set-aside land, giving total production of 1870 kt. Relatively small amounts of oilseed rape are imported and exported which generally result in small changes to the overall balance. [158]

Table 16.1 gives a breakdown of existing UK biodiesel capacity, which amounts to 577 ktpa. Only around 130 ktpa of this total is currently based on OSR. In 2005/05 overall production of OSR in the UK was 1870 kt, mainly for domestic food use.

Table 16.1: Existing UK biodiesel capacity

<table>
<thead>
<tr>
<th>Location</th>
<th>Capacity (ktpa)</th>
<th>Feedstocks</th>
</tr>
</thead>
<tbody>
<tr>
<td>North east</td>
<td>250</td>
<td>Rape/soya/palm in equal</td>
</tr>
<tr>
<td></td>
<td></td>
<td>quantities</td>
</tr>
<tr>
<td>North east</td>
<td>32</td>
<td>Soya at present, jatropha from</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2008</td>
</tr>
<tr>
<td>North west</td>
<td>200</td>
<td>Rape/sunflower/peanut/maize</td>
</tr>
<tr>
<td>Humberside</td>
<td>50</td>
<td>Used vegetable oil</td>
</tr>
<tr>
<td>Scotland</td>
<td>45</td>
<td>Vegetable oil/tallow</td>
</tr>
</tbody>
</table>

Significant biodiesel expansion is already planned and table 16.2 illustrates the projected growth of the biodiesel industry in the UK. Overall plans are for of the order of 1500 ktpa additional capacity. Based on the information below relating to known feedstocks around half of this could potentially be based on oil seed rape, resulting in over 700 ktpa additional capacity for biodiesel production from oilseed rape. This is less than half of current UK oil seed rape production.
<table>
<thead>
<tr>
<th>Planned year</th>
<th>Location</th>
<th>Capacity (ktpa)</th>
<th>Feedstocks</th>
<th>Ancillary facilities</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>2007</td>
<td>Humberside</td>
<td>100</td>
<td>Rape/sunflower/soya/UCO</td>
<td>Existing crusher with 150 kt capacity</td>
<td>1500 farmers signed up for 160 kt OSR from 2006 harvest</td>
</tr>
<tr>
<td></td>
<td>Merseyside</td>
<td>100</td>
<td>Soya then jatropha from 2008</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2008</td>
<td>North east</td>
<td>200</td>
<td>Significant proportion of OSR</td>
<td>New shared oilseed crusher on same site with 250 kt capacity</td>
<td></td>
</tr>
<tr>
<td>North east</td>
<td>200</td>
<td>Significant proportion of OSR</td>
<td>New shared oilseed crusher on same site with 250 kt capacity - meal to be burned to provide energy</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Humberside</td>
<td>100</td>
<td></td>
<td></td>
<td>Currently use neighbouring crusher with 150 kt capacity</td>
<td>Planned increase in capacity to 2007 facility above</td>
</tr>
<tr>
<td>Merseyside</td>
<td>220</td>
<td>Jatropha</td>
<td></td>
<td></td>
<td>Planned increase in capacity to 2007 facility above</td>
</tr>
<tr>
<td>2009</td>
<td>North west</td>
<td>150</td>
<td>UCO</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Scotland</td>
<td>500</td>
<td>NK</td>
<td>Plans for an oilseed crusher nearby with 250kt capacity</td>
<td>Port location – feedstock could be imported</td>
<td></td>
</tr>
</tbody>
</table>
These figures have been used (with some assumptions and interpolating) to produce figure 16.1, which estimates the projected UK biodiesel growth by feedstock.

**Figure 16.1: Projected UK biodiesel growth by feedstock**
17. Wheat

17.1 Background
International alcohol production as a biofuel has, to date, been centred around efforts in the Americas, where the dominant feedstocks have been sugar cane and maize. These are not crops that are particularly suited to the UK climate. Therefore alcohol production is to be based on indigenous crops in the UK other feedstocks must be considered. The production process requires fermentation of starch or sugar to produce alcohol, in much the same way as alcohol is produced for human consumption in the UK at present. This is an area where the UK does have significant expertise, producing significant quantities of spirit and grain whisky. In theory any feedstocks containing starch or sugar could be used, but the forms in which the sugars are present affect the fermentation steps and enzymes used. At present over 90% of whisky production in the UK is based on wheat and there is good reason for this, as wheat produces more harvestable starch than any other UK crop and UK wheat yields are amongst the highest in the world. [161] For current alcohol production in the UK specific varieties with soft grain are sourced from northern Britain, where conditions maximise grain starch content.

Worldwide wheat is the most important cereal crop, with production exceeding that of rice. [162] The grain contains

17.2 Feedstock description
Wheat is a robust annual grass, usually 60-120 cm tall. There are many different species but *Triticum aestivum* (bread wheat) is the most important, the highest yielding and widest ranging, as well as the one most suited to breadmaking.

17.3 Feedstock origin
The origin of *Triticum aestivum* is thought to be somewhere south of the Caspian sea, but its rise to prominence came only after wheat cultivation had spread to more humid areas and during the last two thousand years it has spread to almost all parts of the world where wheat can be grown. [162]

17.4 Environmental and ecological impacts

17.4.1 Crop origin and growth pattern
18.4 million hectares of land are classed as agricultural use in the UK and this is 75% of UK land area. Of this the area dedicated to arable cropping represents less than one third of the UK agricultural land area. The remaining area is dominated by grass and rough grazing for livestock production. The UK cereal area as a whole is now around 3 million ha with wheat dominant at between 1.8 and 2.1 million ha. The main environmental impacts revolve around:

Pesticide use – for wheat this is similar to sugar beet, though much less than in potatoes. Over the past 10 years there has been a decrease in the weight of active substances applied to wheat and a decline in application rates for all groups of pesticides except insecticides. Organo-phosphorus insecticides are now most commonly used in wheat (to control orange blossom midge) Isoproturon, a herbicide
found in ground water, has now been banned, but in recent years preceding the ban a voluntary code of practice lead to fewer reports of isoproturon as a water contaminant.

17.4.2 Energy balance and greenhouse gas impact
Agriculture is a major source of the greenhouse gas nitrous oxide, but cereals pose less risk than root crops and fertilised grassland. If wheat is grown for biofuels rather than food there may be a slight reduction in nitrogen application, reducing greenhouse gas impacts slightly.

17.4.3 Impact on habitat and biodiversity
Cereal stubbles are key habitats for farmland birds. Wheat stubbles are commonly used by species like skylarks. Cereals host many spiders and carabid beetles. Insecticide use poses a risk to these but is minimised when application periods are restricted.

Replacing set-aside with wheat would reduce farmland diversity and have a detrimental impact on farmland birds, but crop stubbles provide a winter resource for birds, which would mitigate these impacts.

17.4.4 Risks associated with agrochemical use
Replacement of set-aside with wheat increases physical inputs of pesticides, fertilisers and energy.

17.4.5 Impact on water courses – fertiliser and nitrates
Fertiliser use – wheat crops pose a relatively low risk of nitrate leaching loss where fertiliser applications are optimised. Phosphate applications on wheat are declining. Biosolids can be applied to wheat crops.

The number of water quality failures caused by pesticides is declining, but very few pesticides used on cereals account for pesticide-related water quality failures.

The replacement of wheat for food with wheat for biofuels may slightly reduce risk of nitrate leaching. When replacing set-aside with wheat for biofuel the risk of nitrate leaching is increased as there are no N applications to uncropped set-aside and no cultivations on long term set-aside.

17.4.6 Impacts on soil
On most soil types there is a low risk of severe soil erosion with most cereal crops compared to root crops and other spring-sown crops. However, there is a slightly higher risk of erosion compared to natural regeneration set-aside

17.5 Production

17.5.1 Objectives
Traditionally UK wheat production has focused on the quality parameters important for animal feeding, and to a lesser extent milling which includes high grain protein content. However, for the bioalcohol industry high grain starch content is more advantageous.

Worldwide 230 Mha of land are under wheat cultivation annually with a mean yield of 2.54 t/ha, giving 585 Mt produced per annum. Yields in the UK are significantly
higher than this, with 8.11 t/ha across 2 million hectares giving 16 Mtpa, and making the UK the third largest producer in the European Union, behind only France and Germany, both of whom have lower yields than the UK. [162]

In 2005/06 nearly 1.9 million hectares of wheat were grown, producing nearly 15 million tonnes of wheat grain. 2.4 million tonnes of this wheat were surplus and available for export.

More than 90% of the UK’s neutral spirit and grain whisky production is from wheat. Specific varieties with soft grain are sourced from northern Britain, where conditions maximise grain starch content. The fuel alcohol market will be larger, cost efficiency will be more crucial and environmental constraints may apply, particularly to maximise greenhouse gas savings with respect to petrol. Thus feedstocks giving higher alcohol yields and increased processing efficiency are beneficial.

Whilst it is important that grain is adequately dried to avoid fungal and mould contamination it is possible that grain with moisture contents greater than 15% may be accepted by fuel alcohol producers at lower penalties than in other markets. Drying wet grain presents a substantial economic cost to growers and it should be possible to store grain at 16% moisture for up to a month.

17.5.2 Agrochemical applications

Requirements for potassium, phosphate and minor nutrients will be the same with wheat for alcohol as for conventional markets, and nutrients should be applied as appropriate for the rotation. N fertiliser is the single most important management factor to be considered when growing wheat for bioethanol due to its large effects on grain yield, alcohol yield as well as GHG emissions and energy balance. Growers should apply the economically optimum amount of N, based on a yield response curve for wheat which is well-defined. At grain prices of £75/t this is about 165 kg/ha, but can increase to 190 kg/ha with lower fertiliser and higher grain prices. Very high yield potential cultivars on high potential sites may justify substantially more. Growers for a milling market need to meet minimum specifications for protein content and so usually apply additional late season N. Higher protein contents reduce alcohol yield. Therefore applying N increases grain yield but increases protein content, which decreases alcohol yield per hectare. Therefore some would claim that maximum alcohol yields per hectare are achieved at 200 kg/ha N, which is higher than the optimum for grain yield. [161] Others would dispute this.

17.5.3 Proposed agronomic regime for modelling purposes.

Taking a benchmark UK feed wheat (on a dry basis) as having 11.5% protein, 69% starch and 3% sugar, the benchmark alcohol yield (at 92% efficiency) can be taken as 435 litres per tonne. Processing yields from recent laboratory tests (using potable methodology) vary between 410 and 480 litres ethanol per tonne. Feedstock quality also affects processing rate and efficiency, particularly by changing the viscosity of intermediaries and residues, but efficiency is rarely estimated. Alcohol production from the best varieties grown in the best UK conditions is likely to exceed 4,000 litres alcohol per hectare. This compares favourably with other cereal-based biofuel production systems in other parts of the world. [161]
17.6 Economics
Wheat made up 1.868 M ha out of 4.427 M ha of arable crops in the UK in 2005. An estimated requirement for 25 million tonnes of petrol in 2010 and the RTFO 5% renewable component in fuels would require 1.25M tonnes of bioethanol, assuming the obligation is equally split between petrol and diesel. One tonne of wheat produces 0.29 tonnes bioethanol, so 3 million tonnes of wheat would be needed per annum. The UK currently has an export surplus of approximately 2 million tonnes of wheat per annum, which could make up much of the requirement, although in reality at least some of the bioethanol will be imported. [161]

Grain yields from wheat in the UK are amongst the highest in the world. The combination of high yielding varieties giving high alcohol yields may provide the UK industry with a competitive advantage. However, costs for production are also high in the UK and there is a need to maximise productivity per unit of cost.

17.7 Social context
Much of the social concerns relating to biofuels revolve around the arguments related to the food vs fuel debate. Wheat is potentially the most controversial feedstock in this respect, as it is a well-known, internationally traded foodstuff, which provides a significant proportion of the world’s food supply. It is argued that utilising the whole crop (rather than just straw) for biofuel production is immoral while some parts of the world go hungry and also that international trade for biofuels, artificially created by subsidised target and incentive programmes, will increase cereal prices, which could price low-income consumers out of the market for staple foods.[158]

A contrary view is that all countries (even poor ones) have land and therefore having reasonably high food prices actually helps poor countries most. It is possible to significantly expand world production by introducing export possibilities from new areas e.g Russia or Brazilian savannah (currently no road access). The key is making sure that the new acreage is taken from the right sort of existing land uses, rather than destroying native habitats and ecologically sensitive areas. There are also many countries where suitable arable land is not currently in use. This could facilitate expansion of grain by around one third of current supply.

17.8 Status and prospects
UK fuel-alcohol production from wheat is expected to begin in 2008. If current plans are realised this requirement will soon add at least 2.5 million tonnes of grain to the 0.7 million tonnes already required for potable alcohol. [161]

Fuel alcohol production from sugar beet will begin in the UK in 2007 and from wheat in 2008. At present new plants are planned in Somerset, Northants, Humberside and Teeside to process about 2.5M tonnes grain into 0.66M tonnes bioethanol, so wheat will be sourced throughout the UK. [158]
### Table 17.1: Planned UK bioethanol capacity

<table>
<thead>
<tr>
<th>Planned year</th>
<th>Location</th>
<th>Capacity (ktpa)</th>
<th>Feedstocks</th>
<th>Operator</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>2007</td>
<td>Norfolk</td>
<td>55</td>
<td>Sugar beet</td>
<td>British Sugar</td>
<td>Using 700 kt sugar beet, producing 180 kt dried pulp</td>
</tr>
<tr>
<td>2008</td>
<td>Teeside</td>
<td>475</td>
<td>Wheat (1500 kt pa)</td>
<td>2 separate plants</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Somerset</td>
<td>110</td>
<td>Wheat (350 kt)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Humberside</td>
<td>100</td>
<td>Wheat (325 ktpa)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Northamptonshire</td>
<td>100</td>
<td>Wheat (300 kt)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2009</td>
<td>Humberside</td>
<td>210</td>
<td>Wheat (600-700)</td>
<td></td>
<td>Use DDGS for CHP onsite</td>
</tr>
<tr>
<td></td>
<td>Teeside</td>
<td>110</td>
<td>Wheat (360 kt)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

#### 17.8.1 Conversion process

Benchmarks proposed for current production of fuel-alcohol from UK feed wheat (dry basis) are 7.4 t/ha grain, 11.5% protein, 69% starch, 3% sugar to yield 435 litres alcohol per tonne or 3,220 litres per hectare. Variation in alcohol production per hectare largely arises in the field through differences in grain yield and starch content; new plant breeding initiatives and better use of N fertilisers should improve these parameters and reduce variation in alcohol yield. Efficiency of fuel alcohol processing can also be enhanced. It is expected that best practice will soon exceed 4,000 litres alcohol per hectare, and that this will continue to increase through new R&D.
18. Jatropha

18.1 Feedstock description
Jatropha curcas (Linnaeus) is a multipurpose bush or small tree belonging to the family of Euphorbiaceae [163]. The plant can be used to prevent and/or control erosion, to reclaim land, grown as a live fence, especially to contain or exclude farm animals and be planted as a commercial crop. It is a native of tropical America, but now thrives in many parts of the tropics and sub-tropics in Africa/Asia (ibid).

18.2 Feedstock origin

18.2.1 Overview
In 2000, Openshaw described *Jatropha curcas* is a multipurpose plant with considerable potential: a tropical plant that can be grown in low to high rainfall areas. [163] Oil can be extracted from the seed, with properties similar to those of palm oil, so it can be used in place of kerosene and diesel. Able to substitute for fuelwood, it has been promoted for rural self sufficiency as regards cooking, lighting and motive power (ibid). Commenting on these claims, Openshaw concluded that more information was needed on the actual and potential markets for Jatropha products and was sceptical of the self-sufficiency claims (ibid).

Jatropha is perhaps unusual among feedstocks in the context of UK bioenergy supply, in that it is being touted not only for large scale plantations for biodiesel, but also for the economic development of small, poorer farmers in the tropics and sub-tropics. As such, its cultivation could in principle provide employment, environmental enhancement and improve quality of life [163]. Since Openshaw’s review in 2000, Jatropha has been the centre of considerable attention. While Pongamia pinnata (Honge or Karanj) and Castor (Erand) also perform well among the 100 or so oil-rich tree species of the tropics / sub-tropics [164], Jatropha Curas is seen as being the most advantageous. Lele [164] lists eight varieties of Jatropha. However, there is little sustainability-related literature on Jatropha. Seven years on from Openshaw, the literature is largely promotional or relates to Jatropha’s energetic or mechanical properties.

Thus Lele [164] lists the advantageous properties of Jatropha:

- Oil yield per hectare is among the highest of tree borne oil seeds.
- It can be grown in areas of low rainfall (500 to 1,000 mm per year) and in problem soils. In high rainfall and irrigated areas too it can be grown with much higher yields. Therefore, it can be grown in most parts of the country. It can be grown in desert areas, with the help of drip irrigation (but it is an expensive system).
- Jatropha / Castor is easy to establish, grows relatively quickly and is hardy.
- Jatropha / Castor plantations have advantage on lands developed on watershed marginal, degraded, fallow, waste and other lands such as along the canals, roads railway tracks, on borders of farmers’ fields as a boundary fence or live hedge in the arid / semi-arid areas and even on slightly alkaline soils. As such it can be used to reclaim waste lands in the forests and outside.
- Jatropha / Castor seeds are easy to collect as they are ready to be plucked after the rainy season and as the plants are not very tall.
- Jatropha / Castor (as an intercropped mix) is not browsed by animals.
- Being rich in nitrogen, the seed cake is an excellent source of plant nutrients.
- Seed production ranges from about 0.4 tons per hectare in first year to over 5 tons per hectare after 3 years.
- The Jatropha plantation starts giving seed in a maximum period of two years after planting, while Castor bears seed in 5 months.
- Raising plants in nurseries, planting and maintaining them and collection of seed are labour intensive activities. Except for the cost of fertiliser and transportation of the plants from a on-site nursery, all the activities in the nurseries and in plantation consist of labour.
- Various parts of the plant are of medicinal value, its bark contains tannin, the flowers attract bees and thus the plant has honey production potential.
- Like all trees, Jatropha / Castor removes carbon from the atmosphere, stores it in the woody tissues and assists in the build up of soil carbon. It is thus environment friendly.
- Jatropha can be established from seeds, 3 months old seedlings and vegetatively from cuttings. Use of branch cutting for propagation is easy and results in rapid growth, but has no tap root, making the plant weak. Castor is grown from seeds only.
- The plant is undemanding in soil type and does not require tillage.

18.3 Agronomy / Silviculture

Jatropha Curcas has undergone rapidly expanding planting in India, Indonesia and Africa. It is a multipurpose bush or small tree belonging to the family of Euphorbiaceae [163]. The plant can be used to prevent and/or control erosion, to reclaim land, grown as a live fence, especially to contain or exclude farm animals and be planted as a commercial crop. It is a native of tropical America, but now thrives in many parts of the tropics and sub-tropics in Africa/Asia (ibid). Jatropha can be established from seed, seedlings and cuttings [165].

Openshaw (ibid) states that the plant has few pests and diseases and will grow under a wide range of rainfall regimes, from 200 to over 1500 mm per annum. In low rainfall areas and in prolonged rainless periods, the plant sheds its leaves as a counter to drought. Its water requirement is relatively low: 1 litre per plant per day [164]. Jatropha is described as easy to establish, grows relatively quickly and is hardy, being drought tolerant. It is not browsed, for its leaves and stems are toxic to animals. After treatment, the seeds or seed cake can be used as an animal feed.

Heller ([166] in [163]) states that if nitrogen is not applied, then flowers may abort and seed production decline. Openshaw refers to an Indian booklet on the management of Jatropha [167] that recommends the addition of farmyard manure and NPK to the planting hole and yearly top dressings of fertilizers, including the seed cake. Observing that the subsistence sector may not be able to afford mineral fertilizers, and/or the distribution system for this may be poor, [163] (ibid: 5) suggests that growing jatropha in combination with nitrogen fixing plants, especially trees, may be the most cost-effective solution (e.g. Prosopis spp in low rainfall areas and Sesbania spp and Leucaena spp where rainfall is above 1,000 mm p.a.).
Lele [164] describes the agronomy of Jatropha in detail as follows.

Nurseries supply seedlings to the farmers and produce seed at the end of the first year (a seedling starts to yield seeds at one year old. Pruning of Jatropha in first two years is important and is highly labour intensive: cheap labour is thus a key factor in the profitability of a plantation. The top of the sapling is cut in the nursery, just before sending it to the plantation. It is pruned twice or thrice in first two years. Due to pruning, there is lesser flowering and fruiting in first two years. After every pruning, 4 branches emerge from the earlier node. To obtain 1kg of seeds after 2 to 3 years, from a single plant, the plant requires at least 24 to 30 secondary or tertiary branches. Each plant is planted at a spacing of 3m X 3m and 1,100 plants would be grown in 1 hectare of Jatropha plantation. Pits are dug manually or using a post hole digger, attached to a tractor. A 20% mortality rate can be assumed. Agronomic cost estimates provided by Lele include those for site preparation, digging of pits, fertilizer & manure, cost of sapling and planting, irrigation, de-weeding, plant protection, maintenance for one year i.e., the stage up to which it will start seed production. There will also be costs of training, awareness generation, monitoring & evaluation.

18.3.1 Oil

Lele [164] envisages that a seed procurement centre for storing procured seed would be sited with an oil extraction plant. Assuming a nursery of 2000 hectares, 7,500 tons of seed would arrive at the procurement centre. He recommends sizing the oil expeller unit at 1 MT/day, 1 MT / hour or 2 MT /hour, with the oil sold first to the local rural market (for e.g. lighting, heating, softening of hide, operating engines for irrigation pumps) and the surplus sold to a transesterification plant.

Jatropha has a high-seed yield that continues to be produced for 30–40 years. Seed production ranges from about 0.4 to over 12 air dry t/ha/y, after five years of growth ([168] in [163]). Sarin et al [165] report the oil content in the Jatropha seeds as around 30–40%. Lele [164] reports oil content as 28% to 30%, with 94% extraction. Lele also states that one hectare of plantation will give 1.6 MT of oil if the soil is average, 0.75 MT if the soil is lateritic, and 1.0 MT if the soil is of the type found in Kutch (Gujarat) [164].

Lele [164] states that analysis of the Jatropha curcas seed shows the following chemical composition:

**Table 18.1: Chemical composition of jatropha**

<table>
<thead>
<tr>
<th>Component</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moisture</td>
<td>6.20 %</td>
</tr>
<tr>
<td>Protein</td>
<td>18.00 %</td>
</tr>
<tr>
<td>Fat</td>
<td>38.00 %</td>
</tr>
<tr>
<td>Carbohydrates</td>
<td>17.00 %</td>
</tr>
<tr>
<td>Fiber</td>
<td>15.50 %</td>
</tr>
<tr>
<td>Ash</td>
<td>5.30 %</td>
</tr>
</tbody>
</table>

The oil content is 25 – 30% in the seeds and 50 – 60% in the kernel. The oil contains 21% saturated fatty acids and 79% unsaturated fatty acids. Jatropha seed-cake contains curcin, a highly toxic protein similar to ricin in Castor. Another poison, a croton resin, occurs in the seeds and causes redness and pustular eruptions of the skin.
The oil has a very high saponification value and is being extensively used for making soap in some countries. Also, the oil is used as lamp oil as it burns without emitting smoke. It is also used as fuel in place of, or along with, Kerosene in stoves [164].

Openshaw [163] notes that while diesel has 8-10 carbon atoms per molecule, Jatropha oil has 16-18. Thus the nut oil is much more viscous than diesel and has a lower ignition quality (cetane number). It requires transesterification with alcohol and a hydroxide, to create a bio-diesel with properties similar to mineral diesel.

18.4 Sustainability

18.4.1 Generic

The main issues underlying sustainability controversy are (a) differing levels of trust in the institutional arrangements (laws, procedures) required to avoid the serious negative impacts of biofuels that are occurring and could occur; and (b) differing approaches to means and ends, with nitrogenous emissions from agriculture overlapping a and b.

Specifically, government and commerce appear to believe that we can avoid future negative impacts through deliberate design (e.g. use of inedible crops, marginal land, more efficient conversion, improved varieties and sustainability certification), and are willing to accept damage in the short term for perceived long term social, commercial and environmental gain. Most NGOs are unwilling to accept any further damage, given the scale and severity of this to date, and do not believe or trust that we can design our way out of the negative impacts. They point to the likelihood of leakage (certificated biofuels pushing less regulated biofuel and agriculture to renewed deforestation) and the very low level of environmental protection in most tropical source countries to date.

The epistemology and definition of sustainability also merits a short discussion. (For a longer discussion of the issues involved in assessing the sustainability to a single sector or entity, see [169]). The concept is subject to a very wide range of interpretations and involves normative judgements as well as environmental science. It is also used rhetorically. Sustainability assessment differs from environmental impact assessment in that it embodies the notion of there being thresholds or limits beyond which natural processes cannot be sustained [169]. Assessing sustainability requires choices as to which natural and social features are to be sustained, and in what form (ibid). These choices remind the analyst that while some consensus on sustainability is usually possible, what is considered sustainable by one person may not be viewed as such by another. This is not to say that the concept is wholly normative, but it is to say that it is significantly normative.

Biofuels and, by association, bioenergy, have an increasingly controversial profile in the news media. Consequently, it is likely that Jatropha will be critiqued not only for its own, direct impacts (which may often be positive, i.e. environmentally and socially beneficial), but simply through association with feedstocks with fewer benefits (such as palm oil). Moreover, there are a wide range of generic issues relating to agriculture for non-food production in a less economically developed country, of which Jatropha production is but one case. In other words, when biomass is imported, the importers engage with conditions and issues in a source country that they may not be directly responsible for, but which nevertheless exist and may well support the importation activity. Such issues include land and water appropriation, the relative merits of sales
for export or local use, and so on. This said, it is also possible to comment on issues specific to Jatropha, and the following provides an overview.

### 18.4.2 Jatropha-specific

The following is extracted from Biofuelwatch et al ([170]), who assert that in India and Africa the planting of Jatropha trees for agrodiesel will threaten remaining forests. Biofuelwatch et al (ibid) state that the Indian government is promoting the rapid expansion of Jatropha monocultures for biodiesel on 50 million hectares of lands classified as ‘wastelands’. While Jatropha is widely promoted as a crop that can grow in dry regions, they note that regular and sufficient rainfall is needed to sustain high yields. In arid and semi-arid areas, fertilisers and irrigation are needed for the first three years. In large parts of India, ground water tables are falling, threatening the future of agriculture over large areas.

The head of the World Institute of Sustainable Energy in Pune, G.M. Pillai, has also warned that promotion of Jatropha for biodiesel is likely to lead to the destruction of primary and secondary forests in India, with serious consequences for biodiversity ([171], in [170]).

Biofuelwatch et al (ibid) state that communities in the Himalayan foothills are extremely concerned that Jatropha will threaten the forest and the biodiversity on which they depend for their livelihoods. In Chhattisgarh, for example, the state government is promoting Jatropha without any feasibility study, even though alien invasive plants are a prime driver for biodiversity losses in the area. The NGO Sutra has warned: “Jatropha is a weedy species and spreads itself very fast leaving lesser grasslands for grazing animals. Some cases have been reported from Chhattisgarh where animals died after eating its leaves.” (The Indian Express, 2006, in [170]).

Indeed, Jatropha will grow almost anywhere in the tropics and subtropics; consequently it has invasive potential when transplanted to new habitats. Western Australia’s Agriculture Protection Board has placed a state-wide ban on two plants being used as sources of biodiesel feedstock. WA claims the Bellyache bush and physic nut (Jatropha Curcas) are both invasive plants, highly toxic to humans and livestock [172]. Both plants are already on the WA declared plants list, but their status has been upgraded to ban them state-wide.

Joshi [171] cites Pillai (ibid) as stating that competition between biodiesel crops and food crops in India must be closely monitored. Joshi [171] notes that Pillai is not alone in warning that a country such as India should not move from producing crops for the public good to crops that ‘benefit only a minority of car-owners and industries.’ Bio diesel is being promoted in India as most people believe that there is enough wasteland available in the country to grow the crop. But, Pillai warns, “in reality, not much wasteland is currently available in India that can be brought under bio diesel crop cultivation”. This view is shared by S H Gade, the man in charge of the bio diesel programme at Pune’s horticulture directorate. “A lot of wasteland in the state of Maharashtra has already been brought under horticulture,” he says.

Joshi [171] also cites H M Kulkarni, project executive, MEDA, as advocating a reality check on specific claims made in published literature that biodiesel crops like jatropha can be grown anywhere and do not require much irrigation. For good yields, commercial crops do require the minimum inputs of irrigation, fertilisers, etc. Kulkarni also disagrees with the claim that bio diesel crops like jatropha can be cultivated on degraded barren land and in drought-prone areas. To make any project
viable, says Kulkarni, certain minimum land area has to be brought under cultivation. “Our experience shows that the minimum area under cultivation should be 200 hectares to make processing economically viable.” Considering the average land size of the individual Indian farmer, this seems possible only under collective farming.

Further, Joshi [171] cites Pillai as having reservations about India’s dependence on jatropha as a low-cost source of bio diesel. “We should be against the promotion of any single crop for bio diesel on a large scale,” he says. He suggests a strategy of multiple and diverse cropping of non-edible tree-borne oilseed that can be developed for bio diesel. Trees like Pongamia pinnata, neem, rubber and castor seeds.

One of the key sustainability debates, on the economic side, is therefore the extent to which the rural poor will benefit from Jatropha cultivation. Lele [164] refers to Jatropha’s potential for rural employment as relating to:

- Plantation of Jatropha curcas
- Collection of Oil bearing seeds
- Processing of seeds to produce oil and seed cake. Processing of cake to get Bio Gas and Bio Fertilizer
- Manufacture of biodiesel

Qualifying this, Openshaw [163] comments that using plant oil for motive power and cooking may lead to the growers and producers indirectly subsidizing the end users and forgoing more profitable markets for the oil and/or other Jatropha products. His comments draw attention to the need to distinguish between cultivating Jatropha in large plantations for export to EU and US markets, and cultivating Jatropha on smaller scales. Despite the potential strengths of Jatropha listed by Lele [164] above, local markets for its products should not be assumed. Thus Openshaw [163] comments that only where diesel and kerosene are scarce, due to poor and intermittent distribution systems and/or smuggling the fuel to other countries occurs, could it be cost effective to produce plant oil as a diesel substitute. Also, kerosene may be scarce because it is used as a diesel substitute or the price is inflated because rural people buy small quantities at a time. In these cases it may be worth while to use plant oil as an illumination (not cooking) fuel in rural areas.

18.5 Significance for UK and EU

18.5.1 Generic context

The Commission proposed in its Renewable Energy Roadmap[173] a binding target of increasing the level of renewable energy in the EU’s overall mix from less than 7% currently to 20% by 2020. Targets beyond 2020 would be assessed in the light of technological progress [174]. The Biofuels Directive [175], requires that biofuels constitute 5.75% of petrol and diesel energy content in member states by 2010.

In the Commission’s view, biofuels are the only available large scale substitute for petrol and diesel in transport [176]. Referring to “the precarious security of supply situation for oil (and thus for the transport sector)”, in 2003 the EU adopted the biofuels directive [175], with the objective of boosting both the production and consumption of biofuels in the EU (ibid). Since then the Commission has set out a comprehensive strategy for developing the biofuels sector ibid. This EU Strategy for
Biofuels includes a range of promotional measures relating to agricultural support and trade reform, research and development support, investigation of environmental impacts in producer countries and biofuel obligations for EC member states.

Matthews [177], advocating a ‘Biopact’ between North and South, estimates that for the Southern hemisphere to meet 20 percent of the OECD fuel demand for transport by the year 2020 would require its current biofuel production to be increased by 17 times, i.e. from 0.5 EJ today to 9 EJ by 2017. To meet this target, the South would have to produce 18 times as much biofuel as does Brazil currently (ibid: 3553). This would equate to the production of 9EJ of energy, equivalent to 432 billion litres of ethanol per year, or 114 billion gallons (US), or 2.5 billion barrels per year; that’s approximately 7 million barrels per day, equivalent in energy terms to approx 5 million barrels of oil per day (ibid: 3553). Matthews further estimates that it would require investments over 10 years of approximately $432 billion to build over 2000 biorefineries (ibid). This assumes standardized, modular ethanol refineries of the type being built by the US firm Cilion, each with an output of 200 million litres of ethanol per year (ibid).

Oil pressed from 4kg of Jatropha seeds is needed to make 1 litre of biodiesel.[178] Jones [179], reporting on D1 Oils, cites values of each Jatropha tree producing an average of 3.5 kilos of beans each year depending on irrigation levels. She says that according to D1’s estimates, if 2,200 Jatropha trees are planted per hectare, each hectare could yield up to 7 tonnes of beans per annum. D1 expects each hectare to deliver about 3,000 litres of biodiesel (ibid). Jones quotes Philip Wood, Chief of Executive of D1 Oils, as stating that with a total of 6 million hectares under option, roughly the same size as two Belgiums, D1 Oils could produce 18 billion litres of biodiesel, which would meet demand expectations in Europe (ibid). However, Jones is correct to point out that the demand for biodiesel is not coming solely from more developed nation markets.

18.5.2 Other current planting estimates (ISIS, 2007)

The Indian Ministry of Rural Development, which is to coordinate the national mission on biofuel when it is approved, estimates that there are already between 500 000 to 600 000 ha of jatropha growing across India. China claims to have 2 million ha of jatropha under cultivation, and announced plans to plant an additional 11 million across its southern states by 2010. Burma has plans to plant several million ha, and the Philippines, and several African countries have initiated large-scale plantations of their own. So far there are 200 000 ha of jatropha in Malawi and 15 000 ha in Zambia, almost all under a formal lease or agreements with the UK-based company D1-Oils.

Notable investments:

TERI (2006): BP & TERI undertake India’s biggest Biofuels Production project: $9.4 million project funded by BP, expected to take 10 years, aims to cultivate around 8,000 hectares of land in the Indian state of Andhra Pradesh, to demonstrate the feasibility of producing biodiesel from Jatropha Curcas. The project will also install the seed crushing, oil extraction and processing equipment required to produce 9 million litres of biodiesel per annum. A full Environmental and Social Impact Assessment of all elements of the supply chain and life cycle analysis of greenhouse gas emissions will be completed as part of the project. TERI will be responsible for the day-to-day management and execution of the project, including the establishment
and implementation of contracts with local farmers or agricultural cooperatives. They will also own and manage the processing facility.

**BP (2007): BP and D1 Oils Form Joint Venture to Develop Jatropha Biodiesel Feedstock:** BP and D1 Oils plc are to form a 50/50 joint venture, to be called D1-BP Fuel Crops Limited, to accelerate the planting of Jatropha curcas. Under the terms of the agreement, BP and D1 Oils intend to invest around $160 million over the next five years. D1 Oils will contribute to the joint venture their 172,000 hectares of existing plantations in India, Southern Africa and South East Asia and the joint venture will have exclusive access to the elite Jatropha seedlings produced through D1 Oils’ plant science programme.

The joint venture will focus on jatropha cultivation in South East Asia, Southern Africa, Central and South America and India. It is anticipated that some one million hectares will be planted over the next four years, with an estimated 300,000 hectares per year thereafter. Investments will be made through directly managed plantations on owned or leased land, which will also provide employment for local communities, and through contract farming and seed purchase agreements.

Jatropha oil produced from the plantations will be used to meet both local biodiesel requirements and for export to markets such as Europe, where domestic feedstock produced from rapeseed and waste oil is unlikely to be sufficient to meet anticipated regulatory led demand for biodiesel of around 11 million tonnes a year from 2010.

‘Once all the planned plantations are established, the joint venture is expected to become the world’s largest commercial producer of jatropha feedstock, producing up to 2 million tonnes of jatropha oil a year,’ says BP’s Phil New” (BP, 2006).

**18.5.3 Constraints**

Aside from land, investment capital, particularly capital availability in Africa, is probably the main present and future constraint on biodiesel supply sourced from Jatropha. Yield is also affected by the level of water and fertiliser inputs.
19. Corn (Maize)
This review of corn (maize) as a feedstock is relatively short, as complementary information is contained in a separate review of ethanol as a feedstock.

19.1 Feedstock description
Dictionary definitions of corn describe it as tall annual cereal grass bearing kernels on large ears; and the principal cereal in Mexico and Central and South America since pre-Columbian times. There are hundreds of varieties of maize. Maize is extensively grown globally as a food crop, for human and animal consumption. With reference to the US, Patzek [180] notes that:

- Corn is the single largest US crop (a record 300 million tonnes of moist corn grain in 2004)
- Corn is harvested in the US from 30 million hectares, roughly the area of Poland or Arizona, and a little less than ¼ of all harvested cropland in the US
- The recent average yield of moist corn grain in the US has been c.8600 kg/ha.

19.2 Production
Finke et al [181] describe maize as very self-sufficient and therefore suitable as a monoculture. They state that its demand for warmth during germination and early development (frost-sensitivity) leads to a late sowing from the end of April until mid-May, depending on the region. As of 1999, there were, for example, 311 maize varieties officially recognised in Germany and adapted to local climatic conditions. Maize hybrids are divided into maturity-groups, for both silage and grain use (ibid: 7). The ripeness number for silage is based on the ripening behaviour of the entire plant and the ripeness number for grain only relates to the maize ear. Maize is cultivated in rows. Depending on the harvesting technology and its use, the distance between the rows is normally 75 cm and the population density 9-13 plants/m2. If no mechanical weed control takes place, the distance between the rows can be reduced to 30 cm [181], ibid.

Maize is harvested in the autumn and late-autumn (September-December). Large, heavy harvesters are used to harvest and chop the maize for silage. Fair-weather is required for harvesting and, in recent years, “stay green” varieties of maize for silage have been used to extend the time for an optimal harvest and a high silage quality, and to avoid soil compaction. Farmers generally grow winter wheat on the same land after the maize harvest, in a rotation, unless maize is grown again ([181], ibid).

DfT [182] summarise the process of producing bioethanol from corn using fermentation as follows. Firstly, the corn must be milled, either by wet milling or dry milling. (The United States is the main producer of alcohol from corn, and the split between the use of wet and dry milling is fairly even). The milling produces co-products of residues which can be sold as animal feed. For wet milling, several types of residues are produced; dry milling produces only one type of animal feed product. Enzymes are used to break down the starches in the corn into C6 sugars which are then fermented and distilled using the same process as for wheat (DfT, ibid).
Figure 19.1 Production of bioethanol from corn using wet or dry milling (source: DfT (2003))
The current conversion efficiency of both wet and dry milling process routes is about 0.55 GJ of ethanol per GJ wheat [183]. The processes are well established but there is some limited scope for efficiency improvements.

19.3 Economics
This section draws on the DfT (2003) study *International resource costs of biodiesel and bioethanol* [182], extracting tables of estimated resource costs in £/GJ and pence/litre respectively for each bioethanol and biodiesel pathway considered by DfT for 2002 and 2020. Resource costs are defined as the costs before taxation of liquid transport fuels delivered to the car driver at a UK filling station. The cost estimates therefore include costs associated with raw materials, processing, distribution and supply of fuels, and take account of any income from the sale of co-products. DfT (ibid) also provide disaggregated costs and a description of associated conversion processes, which are not detailed below.

DfT (ibid) acknowledge that it is very difficult to obtain accurate estimates of the cost of the feedstocks they consider, including corn. With the exception of wood and straw, the feedstocks are sold on the commodity market and their price will thus fluctuate depending on market conditions and expectations of future harvest yields. The price of oilseeds, corn and wheat will also depend on the demand for foodstuffs and any subsidies provided to farmers. Costs to biofuels producers will also depend on the size of the order that they are able to place and the contractual terms agreed (DfT, ibid).

In addition, DfT (ibid) note that ongoing reform of the Common Agricultural Policy (CAP) is likely to affect the cost of biodiesel and bioethanol produced in the EU. New regulations issued in March 2000 after political agreement at the Council level, and the conclusions of the Berlin Summit, will reduce market support of prices for cereals in an attempt to bring farmers more into line with world prices (ibid). Cereals support was reduced from 119.19 Euro/tonne in 2000/2001 to 101.31 Euro/tonne in 2002/2003 but an accompanying increase in direct payments to farmers provided partial compensation for this reduction in support (ibid). DfT (ibid) took the view that price reductions are likely to continue if market support is further reduced by CAP reform in connection with EU enlargement, but that it is not possible to predict the effects of future CAP reform, as negotiations are ongoing.
Table 19.1: Estimated resource costs for 2002 in £/GJ (source: [182])

<table>
<thead>
<tr>
<th>Option &amp; Fuel type</th>
<th>Feedstock</th>
<th>Source</th>
<th>Costs, £/GJ</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Product</td>
</tr>
<tr>
<td>1. Biodiesel</td>
<td>Oil seeds</td>
<td>US</td>
<td>9.86</td>
</tr>
<tr>
<td></td>
<td></td>
<td>EU15</td>
<td>12.22</td>
</tr>
<tr>
<td>2. Biodiesel</td>
<td>Oil seeds - UK production</td>
<td>US</td>
<td>9.86</td>
</tr>
<tr>
<td></td>
<td></td>
<td>EU15</td>
<td>12.22</td>
</tr>
<tr>
<td>3. Bioethanol</td>
<td>Wood - Acid hydrolysis</td>
<td>US</td>
<td>10.18</td>
</tr>
<tr>
<td></td>
<td></td>
<td>EU15</td>
<td>10.18</td>
</tr>
<tr>
<td>4. Bioethanol</td>
<td>Straw - Acid hydrolysis</td>
<td>EU15</td>
<td>19.52</td>
</tr>
<tr>
<td>5. Bioethanol</td>
<td>Wheat</td>
<td>EU15</td>
<td>14.20</td>
</tr>
<tr>
<td>6. Bioethanol</td>
<td>Corn</td>
<td>US</td>
<td>7.41</td>
</tr>
<tr>
<td>7. Bioethanol</td>
<td>Sugar cane</td>
<td>Brazil</td>
<td>5.98</td>
</tr>
<tr>
<td>8. Bioethanol</td>
<td>Sugar cane - UK production</td>
<td>Brazil</td>
<td>20.75</td>
</tr>
<tr>
<td>9. Bioethanol</td>
<td>Sugar beet</td>
<td>EU15</td>
<td>16.16</td>
</tr>
</tbody>
</table>

Table 19.2: Estimated resource costs for 2002 in pence/litre (source [182]DfT)

<table>
<thead>
<tr>
<th>Option &amp; Fuel type</th>
<th>Feedstock</th>
<th>Source</th>
<th>Costs, p/litre</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Product</td>
</tr>
<tr>
<td>1. Biodiesel</td>
<td>Oil seeds</td>
<td>US</td>
<td>33.24</td>
</tr>
<tr>
<td></td>
<td></td>
<td>EU15</td>
<td>41.19</td>
</tr>
<tr>
<td>2. Biodiesel</td>
<td>Oil seeds - UK production</td>
<td>US</td>
<td>33.24</td>
</tr>
<tr>
<td></td>
<td></td>
<td>EU15</td>
<td>41.19</td>
</tr>
<tr>
<td></td>
<td></td>
<td>EU15</td>
<td>41.12</td>
</tr>
<tr>
<td>4. Bioethanol</td>
<td>Straw - Acid hydrolysis</td>
<td>EU15</td>
<td>29.91</td>
</tr>
<tr>
<td>5. Bioethanol</td>
<td>Wheat</td>
<td>EU15</td>
<td>15.61</td>
</tr>
<tr>
<td>6. Bioethanol</td>
<td>Corn</td>
<td>US</td>
<td>12.60</td>
</tr>
<tr>
<td>7. Bioethanol</td>
<td>Sugar cane</td>
<td>Brazil</td>
<td>43.71</td>
</tr>
<tr>
<td>8. Bioethanol</td>
<td>Sugar cane - UK production</td>
<td>Brazil</td>
<td>34.04</td>
</tr>
</tbody>
</table>

Ethanol trade with Brazil is already established, with the Swedish company Alcotra having purchased ethanol from Brazil on a contract to 2007 at a cost of about £6/GJ.
Table 19.3: Estimated resource costs for 2020 in £/GJ (source: [182])

<table>
<thead>
<tr>
<th>Option &amp; Fuel type</th>
<th>Feedstock</th>
<th>Resource Cost £/GJ</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>US</td>
</tr>
<tr>
<td>1. Biodiesel</td>
<td>Oil seeds</td>
<td>10.72</td>
</tr>
<tr>
<td>2. Biodiesel</td>
<td>Oil seeds - UK production</td>
<td>11.58</td>
</tr>
<tr>
<td>3. Bioethanol</td>
<td>Wood - Acid hydrolysis</td>
<td>11.49</td>
</tr>
<tr>
<td>4. Bioethanol</td>
<td>Straw - Acid hydrolysis</td>
<td>20.00</td>
</tr>
<tr>
<td>5. Bioethanol</td>
<td>Wheat</td>
<td>14.17</td>
</tr>
<tr>
<td>6. Bioethanol</td>
<td>Corn</td>
<td>8.15</td>
</tr>
<tr>
<td>7. Bioethanol</td>
<td>Sugar cane</td>
<td>7.88</td>
</tr>
<tr>
<td>8. Bioethanol</td>
<td>Sugar cane - UK production</td>
<td>27.82</td>
</tr>
<tr>
<td>9. Bioethanol</td>
<td>Sugar beet</td>
<td>16.95</td>
</tr>
<tr>
<td>10. Biodiesel</td>
<td>Wood - FT processing</td>
<td>6.49</td>
</tr>
<tr>
<td>11. Biodiesel</td>
<td>Straw - FT processing</td>
<td>6.49</td>
</tr>
<tr>
<td>12. Bioethanol</td>
<td>Wood - Enzymic hydrolysis</td>
<td>10.18</td>
</tr>
<tr>
<td>13. Bioethanol</td>
<td>Straw - Enzymic hydrolysis</td>
<td>10.18</td>
</tr>
</tbody>
</table>
Table 19.4: Estimated resource costs for 2020 in pence/litre (source [182])

<table>
<thead>
<tr>
<th>Option &amp; Fuel type</th>
<th>Feedstock</th>
<th>Resource Cost p/litre</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>US</td>
</tr>
<tr>
<td>1. Biodiesel</td>
<td>Oil seeds</td>
<td>36.12</td>
</tr>
<tr>
<td>2. Biodiesel</td>
<td>Oil seeds - UK production</td>
<td>39.03</td>
</tr>
<tr>
<td>3. Bioethanol</td>
<td>Wood - Acid hydrolysis</td>
<td>24.21</td>
</tr>
<tr>
<td>4. Bioethanol</td>
<td>Straw - Acid hydrolysis</td>
<td>42.12</td>
</tr>
<tr>
<td>5. Bioethanol</td>
<td>Wheat</td>
<td>29.85</td>
</tr>
<tr>
<td>6. Bioethanol</td>
<td>Corn</td>
<td>17.17</td>
</tr>
<tr>
<td>7. Bioethanol</td>
<td>Sugar cane</td>
<td>16.60</td>
</tr>
<tr>
<td>8. Bioethanol</td>
<td>Sugar cane - UK production</td>
<td>58.61</td>
</tr>
<tr>
<td>9. Bioethanol</td>
<td>Sugar beet</td>
<td>35.71</td>
</tr>
<tr>
<td>10. Biodiesel</td>
<td>Wood - FT processing</td>
<td>21.89</td>
</tr>
<tr>
<td>11. Biodiesel</td>
<td>Straw - FT processing</td>
<td>21.89</td>
</tr>
<tr>
<td>12. Bioethanol</td>
<td>Wood - Enzymic hydrolysis</td>
<td>21.45</td>
</tr>
<tr>
<td>13. Bioethanol</td>
<td>Straw - Enzymic hydrolysis</td>
<td>21.45</td>
</tr>
</tbody>
</table>
19.4 Environmental and ecological impacts

The impacts of maize cultivation are similar to those of intensive agriculture generally. The mitigation strategies are also relatively generic. Finke et al, ibid, state that maize cultivation can cause soil erosion on hill-slopes with easily eroded soil. The risk of soil erosion is greater in spring because maize is grown in rows and covers the ground late (ibid). Maize may also require irrigation in the summer, especially in low rainfall areas, which could impact on water sources. Nitrate and herbicide run-off to water courses and groundwater may be a further issue.

Finke et al (ibid) describe the corresponding, mitigation strategies as including:

19.4.1 Weed control
- Use of the new generation of herbicides that are less dangerous to soil creatures.
- The use of herbicides can be restricted by the use of time limits (permitted periods of time).
- Young maize-plants are especially sensitive to competition between the 4 and 6-leaf-stage. Before and after this time, weeds can be tolerated to a greater degree. Later the maize-plants shade the ground so intensively that the growth of weeds is hindered.
- Row culture offers the possibility of mechanical weed control.
- A combination of chemical control in the row (band spraying) and mechanical control between the rows increases the success of weed control.

19.4.2 Fertiliser use
- Assessment of the nutrient content in the farm manure and the soil, to inform the need for additional fertilisation.
- Apply manure at times, rates and with methods that maximise uptake by the maize

19.4.3 Crop rotation/cultivation
- Cover the ground through the winter with catch crops, killed with herbicide before the maize is planted. If water availability permits, this may be planted as an underseed of grasses or legumes.

19.4.4 Soil management
- To improve/maintain the organic matter of the soil, maize seed may be sown into a catch crop cover that has experienced frost over winter or has been destroyed with a non-selective herbicide.

19.4.5 Energy balance

Regarding the energy balance of corn ethanol, the treatment of co-products is critical. Thus DfT (2003) contrast the values in a report by Imperial College for DTI (ICCEPT
2003) and a study by Elsayed et al for DTI (2003), though neither consider corn ethanol as this is unlikely to be produced in the UK. The contrast emphasises the importance of the LCA assumptions. ICCEPT (2003) shows that some pathways to biodiesel and bioethanol have a negative or small positive energy ratio, as shown in the DfT (2003) Table 7.1 below, if co-products are ignored. ICCEPT (2003: iii) argue that allocation can be properly made only once actual plant and systems are in operation, and hence uncertainties and lack of data are resolved. An energy ratio of less than 1.0 indicates that more non-renewably-sourced energy is put into the process than is embodied in the biofuel product.

**DfT [182] Table 19.5: Carbon balances for biofuel production (source: [184])**

<table>
<thead>
<tr>
<th>Process</th>
<th>Energy ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Biodiesel from oil seeds</td>
<td>0.7 - 4.4</td>
</tr>
<tr>
<td>Biodiesel from FT processing of wood</td>
<td>18.1 – 44.3</td>
</tr>
<tr>
<td>Bioethanol from grain</td>
<td>0.9 - 2.6</td>
</tr>
<tr>
<td>Bioethanol from straw</td>
<td>0.8 - 2.4</td>
</tr>
<tr>
<td>Bioethanol from sugar beet</td>
<td>0.7 - 1.8</td>
</tr>
</tbody>
</table>

The ICCEPT report [184] concludes that biodiesel and bioethanol routes are generally energy intensive and significantly favourable energy balances are only achieved when renewable fuels, mainly residues from the biomass resource used, are used to produce energy for the process, and when energy and avoided emissions are allocated to co-products. In the case of corn, these are principally animal feed, including pulp pellets and distiller’s dry / wet grains (DDGS or DWS). In contrast, a report for DTI by Sheffield Hallam University, examining carbon and energy balances for a range of alternative UK biofuel production routes, shows positive energy balances ([185] Table 7.2). Elsayed et al (ibid) did not study ethanol from corn, but did include ethanol from wheat. Study of the latter allocated energy inputs and GHG outputs between wheat straw and wheat grain, bran and coarse powder flour, animal feed and ethanol (ibid: 4.3.15).

**DfT (2003) Table 19.6: Carbon balances for biofuel production [185]**

<table>
<thead>
<tr>
<th>Process</th>
<th>Energy ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Biodiesel from oil seeds</td>
<td>2.3</td>
</tr>
<tr>
<td>Bioethanol from acid hydrolysis of straw</td>
<td>5.6</td>
</tr>
<tr>
<td>Bioethanol from wheat</td>
<td>2.2</td>
</tr>
<tr>
<td>Bioethanol from sugar beet</td>
<td>2.0</td>
</tr>
</tbody>
</table>

Addison [186] provides a summary of scientific literature relating to the energy balance of corn ethanol and associated debate. The Institute for Local Self-Reliance (a US non-profit research organisation) also provides links to studies on the issue [187]. The following sections draw on these sources.
Shapouri et al [188], of the US Department of Agriculture, Economic Research Service, observed that studies of the bioethanol energy balance have been ongoing since the late 1970s and that variations in data and assumptions have resulted in a wide range of estimates. They identify the factors involved in the wide variation and provide their own estimate of a corn ethanol energy ratio as 1.24: for every Btu dedicated to producing ethanol, there is a 24-percent energy gain. They concluded that studies using older data may overestimate energy use because the efficiency of growing corn and converting it to ethanol had improved significantly. They estimated the net energy value of corn ethanol as 16,193 Btu/gal, assuming that fertilizers are produced by modern processing plants, corn is converted in modern ethanol facilities, farmers achieve normal corn yields and energy credits are allocated to co-products. The authors also use energy security as an argument in favour of producing ethanol from domestic corn stocks, as this is seen as using abundant domestic supplies of coal and natural gas to convert corn into a premium liquid fuel that can displace petroleum imports (ibid). Shapouri et al (ibid) compare energy ratios with and without allocation of GHG and energy credits to co-products, and also compare four different methods of co-product allocation. Their value of 1.24 uses the replacement method of co-product allocation, i.e. energy credits are assumed to be equal to the energy that would be expended to produce a substitute product that the ethanol co-product can replace. For example, where corn gluten meal is a co-product of ethanol production, it can replace soybean meal and so is allocated the energy value required to produce the same quantity of soybean meal. (The same principle can be extended to GHG avoidance, but Shapouri et al (ibid) do not study this). The replacement method is conservative relative to co-product allocation on the basis of output market value ($), mass (kg) or energy content (calories) (ibid).

An update to the above work by Shapouri et al [183] found that that the net economic value of corn ethanol has been rising over time due to technological advances in ethanol conversion and increased efficiency in farm production. They show an increase in the energy output: input ratio to 1.34. In the figure below, Wang [189] summarises the upward trend of bioethanol energy balance studies.

Figure 19.2: Corn energy balances (source [189])

*Energy balance here is defined as Btu content a gallon of ethanol minus fossil energy used to produce a gallon of ethanol*
Since the early 1990s, David Pimentel has been a high profile critic of the energy balance, economics and other aspects of corn ethanol and bioenergy (see [190] for a list of references). Pimentel’s (2003) critique of corn bioethanol [190] includes:

- Limited benefits to the U.S. economy and to corn farmers
- 29% more energy used to produce a gallon of ethanol than the energy in a gallon of ethanol.
- Increasing subsidized ethanol production will take more feed from livestock production and is estimated to currently cost consumers an additional $1 billion per year.
- Corn production causes more total soil erosion, uses more insecticides, herbicides, and nitrogen fertilizers than any other crop.
- Diverting human food resources to ethanol raise major ethical questions.
- Subsidized ethanol produced from U.S. corn is not a renewable energy source.

With respect to the energy balance, Pimentel’s general point is that all energy inputs to the ethanol system need to be included in the assessment. This issue of system boundary is at the heart of the debate. Pimentel [190] accepts the principle of co-production of DDG, but by his calculations this only reduces the negative energy balance from 29% to 20%. Some of Pimentel’s data sources are relatively old, but it is not clear to what extent this might account for his differing conclusions. Indeed, Pimentel makes the same point about some of the data sourced for Shapouri et al [183]. Without returning to the flow sheets of the systems involved, it is not possible to be sure why Pimentel finds a negative energy balance, but it does appear to be the inclusion of a wider range of inputs, particularly machinery and plant, which Shapouri et al (2002) ignore. In terms of other aspects of the system, for example, Pimentel also comments on the energy intensity of producing hybrid seeds relative to the seed yielded from the crop.

Patzek [180] extends the critique by providing a thermodynamic and carbon-cycle informed perspective of the corn-ethanol biofuel cycle. As Pimentel, he indicates that more fossil energy is used to produce ethanol from corn than the ethanol’s calorific value. He also observes that production of ethanol from whole plants would be unsustainable, as it effectively mines soil humus through avoiding the return of plant-based carbon. He cites Pimentel [180] as observing that good field practices and continuous use of synthetic fertilisers can maintain soil humus at constant levels, and that these practices may include: crop rotation for nitrogen fixing; corn stover decomposition in the field to conserve soil nutrients and limit erosion; and moderate or no soil tilling. Wheaton et al (191 in [180]), writing for agricultural extension purposes on corn silage, estimate that a corn crop harvested as silage removes more than twice as much nitrogen, three times as much phosphorus and 10 times as much potassium as a corn crop harvested for grain.

Patzek [180] calculates that in 2004, corn ethanol production in the US generated 11 million tonnes of CO\textsubscript{2} more than would have been generated by burning gasoline with 115% of the calorific value of that ethanol. He calculates the cumulative exergy (available free energy) consumed in corn farming and ethanol production, and estimates the minimum amount of work necessary to restore the key non-renewable resources consumed by the industrial corn-ethanol cycle. This amount of work is compared with the maximum useful work obtained from the industrial corn-ethanol cycle. Patzek finds that if the corn ethanol exergy is used to power a car engine, the
minimum restoration work is about 7 times the maximum useful work from the cycle. This ratio drops down to 2.4, if an ideal (but nonexistent) fuel cell is used to process the ethanol. Patzek estimates that the U.S. taxpayer subsidies of the industrial corn-ethanol cycle at $3.3 billion in 2004. The parallel subsidies by the environment are estimated at $1.9 billion in 2004, excluding the restoration costs of aquifers, streams and rivers, and the Gulf of Mexico. Finally, given that thermodynamic 'inefficiencies' would likely be found of other energy options, Pastek estimates for comparison that (per year and unit area) inefficient solar cells could produce c.100 times more electricity than corn ethanol.

Patzek identifies the items included and excluded from key LCA studies of the US corn ethanol energy balance and justifies his own system boundary. For example, he excludes the machinery that Shapouri et al (2002) also exclude but that Pimentel includes. He also takes account of weather differences across states and their implication for energy use. Nevertheless, he finds little disagreement between studies, in terms of the estimates of the total energy used to produce ethanol from corn: all are close to 15 MJ/L EtOH, as shown in his Figure 19 (reproduced as figure 19.3 below).

Figure 19.3: The average fossil energy inputs to ethanol production in a wet milling plant. (source: [180])

In figure 19.4 (reproducing [180]Patzek (2004: Figure 19)) below, the two or three leftmost parts of each bar represent the specific fossil energy used in corn farming and ethanol production. The fossil energy inputs into ethanol production are the sum of the green part and the blue energy credit part for some authors. The rightmost part is the calorific value of corn grain harvested from 1 hectare. The total lengths of the horizontal bars represent all energy inputs into ethanol production. The horizontal lines with the vertical anchors represent the calorific value of ethanol obtained from one hectare of corn. Patzek’s Figure 19.3 shows the difference that energy credits make, regarding the balance of fossil energy input to ethanol energy output (neglecting the energy costs of environmental damage). The figure also shows that a large fraction of the total energy inputs into ethanol production (embodied in the corn, pink section) is dissipated on fermentation, distillation and farming (ibid).
Figure 19.4: The overall energy balance of ethanol production. (source: [180] Figure 19)

Figure 19.5 (Patzek’s Figure 20 (ibid)), below, shows the fossil energy gain or loss in more detail, without the more revealing context of the corn energy. Should co-products be considered a legitimate part of the energy/emissions accounting process? Arguably this should only be the case if the co-products do in fact substitute for other, equivalent production. How could this be determined? Perhaps if the firms involved demonstrably won market share at the expense of other firms? It would seem reasonable that the onus should be on the producer to demonstrate this, rather than it being assumed. Patzek’s argument is different: it is that all corn by-products need to be returned to the land to replenish it and to avoid slow mineral/metal mining. His implicit additional argument is that substitution by petrochemical fertiliser is not sustainable. Perhaps one might argue that the return of human/animal excreta to the land, supplying an equivalent mass of minerals/metal would suffice, but this would only be sustainable if not at the expense of return of manure/sewage to some other area of productive land.

Figure 19.5: Fossil energy gain/loss in corn ethanol production (reproduction of [180] Figure 20)
Figure 19.6 (Patzek’s Figure 39) takes a whole system approach to calculating CO$_2$e. The CO$_2$ emissions from the energy-equivalent amounts of methane, gasoline and diesel fuel were increased by 17% to account for their recovery, transport, and refinement. Patzek [180](2004: 49-50) concludes, inter alia, that:

- 1 ha of industrial corn-for-ethanol generates 8,955 kg of equivalent CO$_2$ from the fossil fuel inputs and humus oxidation.
- If the amount of gasoline with the energy content of 117% of 2,498 kg EtOH/ha obtained on average from corn were burned, it would generate 5,817 kg of CO$_2$.

Figure 19.6: The total equivalent CO$_2$ emissions from the consumption of nonrenewable resources by the industrial corn-ethanol cycle (reproduction of [180] Figure 39)

At the time of this review, Zah et al [33] is the most recent, wide-ranging LCA of biofuels, undertaken as a basis for granting an exemption from the excise duty on fossil fuels in Switzerland. In addition, the impacts of biofuel use are compared with other bioenergy applications, such as the generation of electricity and heat. The study uses the Swiss life cycle inventory database EcoInvent, relating to Switzerland and Western Europe. However, it is important to know that the study goes beyond the LCA inventory stage to the level of impact indication, which adds normative dimensions via impact weighting and choice of indication method (in addition to earlier decisions regarding system boundary, which is a normative stage of all LCA).

The LCA used two methods: one was the Swiss method of ecological scarcity (Environmental Impact Points, UBP 06), which evaluates the difference between
environmental impacts and legal limits [192]; i.e. the impacts of the life cycle inventory items are characterised in terms of their contribution towards a breach in regulated limits, e.g. for air and water quality. The other is the European Eco-indicator 99 method commissioned by the Dutch Ministry of Housing, Spatial Planning and the Environment [193], which quantifies the damage done to human health and ecosystems (i.e. it is not limited only to environmental indication of impacts regulated by law). Both methods show the same results: in the case of tropical agriculture it is primarily the clear-cutting and burning of rainforests that releases the largest quantities of CO2, causes an increase in air pollution and has ‘massive’ impacts on biodiversity. In the moderate latitudes it is partly the lower crop yields, partly the intensive fertilizer use and mechanical tilling of the soil that are the causes of a bad environmental evaluation. The study shows in sensitivity analysis how, for instance, a prohibition of clear-cutting would affect the LCA of biodiesel made from palm oil.

Zah et al [33] (ibid) found that most of the environmental impacts of biofuels can be attributed to the agricultural cultivation of the feedstocks. The environmental impact from fuel processing is usually much lower, the environmental impact from the transport from the production site to Swiss filling stations is even less, even when the biofuels are produced overseas. The study shows that with most biofuels there is a trade-off between minimizing greenhouse gases (GHG emissions) and lower total environmental impacts. Thus while GHG emissions can be reduced by more than 30% with several biofuels, most of the supply paths show greater impacts than petrol for various other environmental indicators. Zah et al (ibid) conclude that it is particularly the use of biogenic wastes, grasses and wood that brings a reduction in environmental impact as compared with petrol.

Figure 2 below, from Zah et al (ibid) compares the greenhouse gases emitted by biofuels and fossil fuels (petrol and diesel, EURO3) on a kg per passenger km basis. US corn ethanol performs little better than petrol and worse than diesel. Figure 3 below from Zah et al (ibid) shows the whole environmental impact using the LCA impact assessment method of ecological scarcity (UBP 06). In general, although the environmental impacts of vehicle operation (dark grey) are much higher when fossil fuel is used, this is outweighed by the high environmental impacts of agricultural production. The causes of this are soil acidification and excessive fertilizer use in European and Swiss agriculture (ibid). In the case of tropical agriculture, the environmental impact arises from biodiversity loss, air pollution caused by clear-cutting and the toxicity of pesticides. (The very high impact of Swiss potatoes can be explained by the high weighting placed on nutrient leaching. The very high values for rye taken from European production are explained by the low harvest yield of rye in Europe (ibid). On the positive side, the lower impacts of waste vegetable oils, wood-ethanol and methane relative to the fossil transport fuels are notable.

The tropically sourced biofuels have high smog impacts because the cultivation areas are often accessed by means of clear-cutting or - in the case of bioethanol from sugar cane - the dry leaves are burned off before the harvest. Excessive fertilizer use was higher by several factors in the cases of agricultural processes compared to fossil fuels. (Though in the cases of Brazilian sugar cane and Malaysian palm oil, these values can be low). Ecotoxicity peaks with cultivation on clear-cut areas, due to the high toxicological evaluation of acetone emissions. The only biofuels that performed better than petrol across all environmental impacts were methyl ester made from waste cooking oil and methane from sewage and biowaste.
Figure 19.6: Comparison of the greenhouse gases emitted by biofuels and fossil fuels (petrol and diesel, EURO3) (source: [33] Figure 2)
Figure 19.7: Aggregated environmental impact (method of ecological scarcity, UBP 06) of bio fuels in comparison with fossil fuels (source: [33] Figure 3)
Figure 19.8 shows overall environmental Life Cycle Assessment of all unblended biofuels studied in comparison to fossil reference fuels. In the figure, GWP = greenhouse warming potential, CED = cumulated non-renewable energy demand, SMOG = summer smog potential, EUTR = excessive fertilizer use. The reference fuel ( = 100%) is petrol EURO3 in each case. The biofuels are shown towards the left, ranked by their respective GHG emission reductions. Fuels that have a total GHG emission reduction of more than 50% compared to petrol are shown in green; those with GHG emissions reductions of more than 30% are in yellow; and those with GHG emissions reductions of less than 30% are red. In the other diagrams, green = better than reference; red = worse than reference. Cross-hatched fields = production paths from waste materials or residue.

Figure 19.8: Overall environmental Life Cycle Assessment of all unblended biofuels studied, in comparison to fossil reference (source: [33] Figure 4)
In terms of GHG emissions, one can see in Figure 19.8 above that US corn ethanol ranks only worse than rye and potato ethanol and soya diesel, which correlates with the same ranking on cumulative non-renewable energy consumption. The contribution to smog by US corn ethanol is marginally worse than Euro 3 petrol and the contribution to eutrophication is of course a lot worse. The summary diagram on the far right of Figure 4 aggregates all of the impacts, via the points method of UB6.

Figure 19.9 summarises the GHG emissions and overall environmental evaluation of all fuels studied. The green area means a better evaluation than the fossil reference both as regards GHG emissions and in the overall environmental evaluation. The figures show that there are production paths for all fuels in the green area; however, most of those “green” production paths are based on waste materials and residue. Bioethanol from Brazilian sugar cane shows very different evaluations depending on whether UBP 06 or Eco-indicator 99 was used. The cause of this is the pesticide Daconate, which contains a lot of arsenic, a chemical in this study only to be found in the inventory of sugar cane cultivation and that causes high ecotoxicology readings when evaluated using Eco-indicator 99. The great differences in bioethanol from potatoes can be explained, on the other hand, through the great importance attached to nutrient leaching in the UBP 06 method (ibid).

Figure 19.9: Two-dimensional representation of GHG emissions and overall environmental impact (Eco-indicator 99) (source: [33]: Figure 7)
Values are relative to petrol. The green area borders a zone of both lower GHG emissions and lower overall environmental impact relative to petrol. The figure lends support to, inter alia, a lignocellulosic route to ethanol. It does not lend support to US corn ethanol as a petrol substitute, nor to Brazilian sugarcane. Malaysian oil palm performs better than US corn ethanol, particularly in terms of GHG emissions. Brazilian sugarcane does, though, have the highest MJ/ha value (i.e. it permits the highest ‘mileage’ for a given area cultivated).

19.5 Social context
Corn ethanol is produced within a regime of agricultural subsidies and intensive, mechanised agriculture. This renders it contested from the outset. The social context is thus similar to that of industrialised agriculture. In the EU at least, fuel-food competition for land is probably more important for arable crops (wheat, corn, sugar) than for woody crops, which can be grown in less favourable soil and climatic conditions [182]. In terms of public perceptions, LCA studies point to a marginal or negative energy yield for corn bioethanol (discussed above). These factors are important with regard to corn as a bioethanol feedstock, not least because they are strong influences on the opinions of critical observers.

19.6 Applications
Describing the German situation, but of wide applicability, Finke et al [181] describe maize production as being otherwise used for feed for cows, pigs and poultry (maize for silage including green-maize, grain maize, corn cob mix, maize coarse meal with husks). As well as being used for producing sugar, grain is also used by the food industry to produce maize-meal-products, snacks, cornflakes etc., and in pharmaceutical processes. As a renewable raw material, maize starch is used in the manufacture of paper and cardboard (it is an important additive in wastepaper processing). New packing and impact protection materials are produced in new extraction moulding procedures from maize-semolina (Finke et al, ibid: 2).

19.7 Constraints
As corn can be cultivated relatively quickly, current production is principally limited by the production cost of, and hence the return potentially available from, corn ethanol relative to alternative feedstocks. In future, it may be that the cost of the high fossil fuel inputs (mineral oil price) will raise the cost differential relative to Brazilian sugarcane and suppress supply; the role of subsidies and trade barriers is critical. In some countries or regions, particularly Europe, sustainability certification may also screen out feedstocks with low GHG savings, limiting both subsidies to and demand for corn bioethanol. On the other hand, lignocellulosic technology would increase supply and mitigate against concerns over low GHG efficiency.

19.8 Conclusions
Corn ethanol, principally produced in the USA, but also potentially produced in quantity in Eastern Europe, does not perform well environmentally relative to other biofuel options. Indeed, its GHG performance relative to fossil energy inputs is only positive when (within LCA) its production system is narrowly scoped and co-products are included. Economically, corn ethanol has been criticised for being highly subsidised but of little additional benefit to farmers. Socially, corn ethanol fits easily
with existing agro-industrial production systems. The importance of corn ethanol to the UK is difficult to determine but it would be reasonable to assume that, in terms of a global biofuels market, its contribution will be modest relative to Brazilian sugarcane, with the US continuing to consume its production domestically.
20. Palm Oil

20.1 Feedstock description

The cultivated oil palm (Elais guineensis Jacq.) is native to West Africa and was traditionally used to make foodstuff, medicines, woven material and wine. Today, oil palm is cultivated in large-scale plantations throughout the tropics, and produces two of the major oils traded in the edible global oils and fats market: Crude Palm Oil (CPO) and Palm Kernel Oil (PKO).

There have been more than 350 oil-bearing crops identified, although only a handful have been considered as potential alternatives for diesel, including soybean, palm, sunflower and rapeseed [194]. Although soy oil has traditionally been the world’s most important vegetable oil, commanding around 30 percent of the global market share, it is slowly losing the market to palm oil [195]. Table 1 shows the world consumption of vegetable and marine oil between 1998 and 2003.

Table 20.1 World consumption of vegetable and marine oil (million metric tonnes)

<table>
<thead>
<tr>
<th>Oil Crop</th>
<th>Year 1998</th>
<th>1999</th>
<th>2000</th>
<th>2001</th>
<th>2002</th>
<th>2003</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soybean</td>
<td>23.5</td>
<td>24.5</td>
<td>26.0</td>
<td>26.6</td>
<td>27.2</td>
<td>27.9</td>
</tr>
<tr>
<td>Palm</td>
<td>18.5</td>
<td>21.2</td>
<td>23.5</td>
<td>24.8</td>
<td>26.3</td>
<td>27.8</td>
</tr>
<tr>
<td>Rapeseed</td>
<td>12.5</td>
<td>13.3</td>
<td>13.1</td>
<td>12.8</td>
<td>12.5</td>
<td>12.1</td>
</tr>
<tr>
<td>Sunflower seed</td>
<td>9.2</td>
<td>9.5</td>
<td>8.6</td>
<td>8.4</td>
<td>8.2</td>
<td>8.0</td>
</tr>
<tr>
<td>Peanut</td>
<td>4.5</td>
<td>4.3</td>
<td>4.2</td>
<td>4.7</td>
<td>5.3</td>
<td>5.8</td>
</tr>
<tr>
<td>Cottonseed</td>
<td>3.7</td>
<td>3.7</td>
<td>3.6</td>
<td>4.0</td>
<td>4.4</td>
<td>4.9</td>
</tr>
<tr>
<td>Coconut</td>
<td>3.2</td>
<td>3.2</td>
<td>3.3</td>
<td>3.5</td>
<td>3.7</td>
<td>3.9</td>
</tr>
<tr>
<td>Palm kernel</td>
<td>2.3</td>
<td>2.6</td>
<td>2.7</td>
<td>3.1</td>
<td>3.5</td>
<td>3.7</td>
</tr>
<tr>
<td>Olive</td>
<td>2.2</td>
<td>2.4</td>
<td>2.5</td>
<td>2.6</td>
<td>2.7</td>
<td>2.8</td>
</tr>
<tr>
<td>Fish</td>
<td>1.2</td>
<td>1.2</td>
<td>1.2</td>
<td>1.3</td>
<td>1.3</td>
<td>1.4</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>80.8</strong></td>
<td><strong>85.9</strong></td>
<td><strong>88.7</strong></td>
<td><strong>91.8</strong></td>
<td><strong>95.1</strong></td>
<td><strong>98.3</strong></td>
</tr>
</tbody>
</table>

Source: [194]

The commercial value of oil palm lies mainly in the oil that can be obtained from the fruit. The oil palm fruit is the size of a small plum and grows in bunches of up to 2000 fruits, which collectively weigh between 10 - 20kg. The fruit consists of a hard nut, the kernel, inside a shell, the endocarp, which is surrounded by a red fleshy layer, the mesocarp. Oil is extracted from both the kernel, known as Palm Kernel Oil (PKO), and the mesocarp, known as Crude Palm Oil (CPO). CPO is edible and is considered the primary product of the oil palm. Today CPO is widely used and is found in one in ten food products. PKE is used in the oleochemical industry, which produces chemical feedstocks for non-edible products such as soap and cosmetics. The two oils differ from one another chemically, physically and nutritionally [196].

In addition to the oils obtained from the fruit, oil palm produces a large number of by-products, including trunk, fibres from empty fruit bunches and fronds. These by-products have a number of different uses and can be processed to produce value-added products such as bioplastics, plywood and animal feed. The waste effluent from the milling process, palm oil mill effluent (POME), can also be converted to produce energy and fertilisers [197]. The use of palm kernel expeller (PKE) as a
biomass feedstock is discussed in another chapter; this chapter focuses on the use of CPO and PKO as biodiesel feedstocks.

This paper reviews the origin, production and economics of oil palm cultivation, before considering specific environmental and social sustainability concerns. Due to the sheer scale of production in Indonesia and Malaysia, which together account for more than 83 percent of global production [198], this review focuses on these two countries.

20.2 Feedstock origin

The oil palms comprise two species of the palm family. The African oil palm, *Elaeis guineensis* Jacq, is native to West Africa and is found growing from Angola to Gambia. The American oil palm, *Elaeis oleifera*, is found in Central and South America. This paper focuses on the cultivated African oil palm, which was introduced to Java by the Dutch in 1848 and to then Malaya by the British in the 1870s [196, 199]. The African oil palm is now cultivated throughout the tropics in regions within 10 degrees either side of the equator.

20.3 Production

There are several stages in the establishment of an oil palm plantation, guided by standard practices [199]. Table 20.2 outlines the key requirements of oil palms.

<table>
<thead>
<tr>
<th>Soil</th>
<th>Water</th>
<th>Nutrients</th>
<th>Climate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Palm oil Good drainage; pH between 4 and 7; soil flat, rich and deep</td>
<td>Even distribution of rainfall between 1,800 and 5,000 mm throughout the year</td>
<td>Low</td>
<td>Tropical and subtropical climate with temperature requirement of 25-32°C</td>
</tr>
</tbody>
</table>

The first stage is preparation of the land; in Malaysia a ‘zero-burn’ policy prohibits the burning of old palms so the vegetation is allowed to decompose naturally. The second stage involves establishing and digging planting holes, which are then filled with fertiliser. Seedlings, which have been established in nurseries, are then placed in the planting holes in rows with a distance of 9 metres between any two seedlings. Oil palms are planted in a triangular planting pattern to allow maximum penetration of sunlight and thus maximum yields; planting density works out to around 148 palms per hectare (ibid). Ground cover is established by planting cover crops such as legumes, in order to prevent soil erosion and the growth of weeds, thus reducing the need for agrochemicals [201]. Between 2.5 to 5 years later, the oil palms begin to produce fruit bunches of a sufficient size and number to begin harvesting.

Upon harvesting, the ripe fruit bunches are sent to a palm oil mill for oil extraction. The two oils, Crude Palm Oil (CPO) and Palm Kernel Oil (PKO), are extracted by separation at different stages of the milling process. In the mill the fruits are sterilised, removed from the fruit bunches and crushed to extract the CPO. The CPO contains impurities, such as fruit fibres and nut shells, which are removed through a purification process before undergoing physical refining to produce the oil product traded on global markets. Meanwhile, the nut shells are processed to separate the
kernels from the shell; this process produces PKO and expeller cake, which is used for animal feed [196].

**Figure 20.1. Overview of the oil palm production chain**

Source: [202]
Oils account for only 10 percent of the total dry biomass produced by the oil palm; the remaining 90 percent represents a source of cellulosic materials that are underused commercially. Basiron [199] argues that the development of second generation biofuels, based on the conversion of cellulosic fibres, makes the oil palm even more attractive as a source of renewable energy.

### 20.3.1 Global production of palm oil

Over the past few decades, global production and trade in palm oil has grown rapidly. Although the production of other key oilseed crops, such as soybean, rapeseed and sunflower, has also been increasing steadily over the same period, the growth rate of palm oil has risen much more rapidly [203]. Production of palm oil has increased from less than 3 million tonnes in 1974 to almost 40 million tonnes in 2005 [204]. Today, palm oil constitutes 27 percent of total global production of oils and fats, and almost 30 percent of global vegetable oil consumption [194, 196]. Table 3 presents current data for global production of the major vegetable oils.
Table 20.3 Global vegetable oil production, 2006

<table>
<thead>
<tr>
<th>Oil crop</th>
<th>Production (million tonnes)</th>
<th>Percentage of total production</th>
<th>Average yield (tonnes/ha/year)</th>
<th>oil Total area (million ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oil Palm</td>
<td>36.90</td>
<td>35.90</td>
<td>3.74</td>
<td>9.86</td>
</tr>
<tr>
<td>Soybean</td>
<td>35.19</td>
<td>34.24</td>
<td>0.38</td>
<td>92.63</td>
</tr>
<tr>
<td>Rapeseed</td>
<td>18.34</td>
<td>17.84</td>
<td>0.67</td>
<td>27.29</td>
</tr>
<tr>
<td>Sunflower</td>
<td>11.09</td>
<td>10.79</td>
<td>0.48</td>
<td>22.95</td>
</tr>
</tbody>
</table>

Source: [197]

Today, global production and trade in palm oil is dominated by two countries, Malaysia and Indonesia, which together account for 85 percent of global palm oil production [204, 205]. Malaysia was the first country to establish an oil palm industry and has traditionally been the leading producer of palm oil [200]. However, rapid plantation growth in Indonesia means that it is expected to overtake Malaysia in terms of production by 2010 [206]. Table 20.4 and figure 20.2 present the changes in production in the major palm oil producing countries between 1990 and 2005.

Table 20.4 Palm oil production in the top ten producer countries, 1990 to 2005

<table>
<thead>
<tr>
<th>Year (million tonnes)</th>
<th>1990</th>
<th>1995</th>
<th>2000</th>
<th>2005</th>
</tr>
</thead>
<tbody>
<tr>
<td>China</td>
<td>0.18</td>
<td>0.20</td>
<td>0.21</td>
<td>0.23</td>
</tr>
<tr>
<td>Columbia</td>
<td>0.25</td>
<td>0.39</td>
<td>0.52</td>
<td>0.67</td>
</tr>
<tr>
<td>Congo, Dem Republic</td>
<td>0.18</td>
<td>0.20</td>
<td>0.17</td>
<td>0.18</td>
</tr>
<tr>
<td>Cote d’Ivoire</td>
<td>0.25</td>
<td>0.27</td>
<td>0.28</td>
<td>0.32</td>
</tr>
<tr>
<td>Ecuador</td>
<td>0.15</td>
<td>0.18</td>
<td>0.22</td>
<td>0.29</td>
</tr>
<tr>
<td>Ghana</td>
<td>0.09</td>
<td>0.10</td>
<td>0.11</td>
<td>0.12</td>
</tr>
<tr>
<td>Indonesia</td>
<td>2.41</td>
<td>4.48</td>
<td>6.86</td>
<td>14.07</td>
</tr>
<tr>
<td>Malaysia</td>
<td>6.09</td>
<td>7.81</td>
<td>10.84</td>
<td>14.96</td>
</tr>
<tr>
<td>Nigeria</td>
<td>0.73</td>
<td>0.86</td>
<td>0.90</td>
<td>1.17</td>
</tr>
<tr>
<td>Thailand</td>
<td>0.23</td>
<td>0.37</td>
<td>0.53</td>
<td>0.69</td>
</tr>
<tr>
<td>World total</td>
<td>11.45</td>
<td>15.91</td>
<td>22.05</td>
<td>34.33</td>
</tr>
</tbody>
</table>

Source: FAO, 2008
Figure 20.2. Palm oil production by producer country as a percentage of global production, 1990 to 2005

Production of palm kernel oil is also dominated by the Malaysia and Indonesia, which in 2005 accounted for 45 and 33 percent of global production respectively. Table 20.5 and figure 20.2 illustrate the share of palm kernel oil produced by the major producing countries between 1990 and 2005.

Table 20.5 Palm kernel oil production in the top ten producer countries, 1990 to 2005

<table>
<thead>
<tr>
<th>Year (tonnes)</th>
<th>1990</th>
<th>1995</th>
<th>2000</th>
<th>2005</th>
</tr>
</thead>
<tbody>
<tr>
<td>China</td>
<td>21,600</td>
<td>23,535</td>
<td>25,397</td>
<td>28,434</td>
</tr>
<tr>
<td>Colombia</td>
<td>20,824</td>
<td>28,744</td>
<td>45,432</td>
<td>63,726</td>
</tr>
<tr>
<td>Congo, Dem Republic</td>
<td>33,467</td>
<td>36,260</td>
<td>32,830</td>
<td>39,690</td>
</tr>
<tr>
<td>Côte d'Ivoire</td>
<td>15,372</td>
<td>13,549</td>
<td>20,441</td>
<td>22,420</td>
</tr>
<tr>
<td>Ecuador</td>
<td>11,282</td>
<td>13,496</td>
<td>17,500</td>
<td>28,800</td>
</tr>
<tr>
<td>Ghana</td>
<td>7,950</td>
<td>10,110</td>
<td>14,600</td>
<td>20,700</td>
</tr>
<tr>
<td>Indonesia</td>
<td>305,000</td>
<td>427,696</td>
<td>717,800</td>
<td>1,321,650</td>
</tr>
<tr>
<td>Malaysia</td>
<td>827,233</td>
<td>1,036,538</td>
<td>1,385,400</td>
<td>1,842,600</td>
</tr>
<tr>
<td>Nigeria</td>
<td>159,538</td>
<td>244,517</td>
<td>196,054</td>
<td>281,429</td>
</tr>
<tr>
<td>Thailand</td>
<td>21,412</td>
<td>35,101</td>
<td>51,859</td>
<td>72,984</td>
</tr>
<tr>
<td>World total</td>
<td>1,674,208</td>
<td>2,072,747</td>
<td>2,772,601</td>
<td>4,025,642</td>
</tr>
</tbody>
</table>

The increase in the production of palm oil and palm kernel oil over the past few decades has been due to rapid expansion in the area planted with oil palm, rather than to increases in yield [205]. The majority of this expansion has occurred in the two top
palm oil producing countries, Malaysia and Indonesia, all too often at the detriment of natural habitats and forests. It should be noted that estimates of areas under cultivation of oil palm vary widely, largely because much of the expansion has occurred illegally. Table 5 and 6 present the changes in oil palm acreage and yield.

**Table 20.5 Oil palm mature areas (million hectares)**

<table>
<thead>
<tr>
<th>Year</th>
<th>1990</th>
<th>1995</th>
<th>2000</th>
<th>2005</th>
</tr>
</thead>
<tbody>
<tr>
<td>Indonesia</td>
<td>0.73</td>
<td>1.24</td>
<td>2.52</td>
<td>3.91</td>
</tr>
<tr>
<td>Malaysia</td>
<td>1.75</td>
<td>2.24</td>
<td>2.94</td>
<td>3.63</td>
</tr>
<tr>
<td>Rest of the world</td>
<td>1.30</td>
<td>1.40</td>
<td>1.56</td>
<td>1.89</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>3.77</strong></td>
<td><strong>4.88</strong></td>
<td><strong>7.02</strong></td>
<td><strong>9.42</strong></td>
</tr>
</tbody>
</table>

Source: [205]

Table 20.5 reveals that oil palm plantation areas in Malaysia expanded from 1.75 million hectares (Mha) in 1990 to 3.63 Mha in 2006. In Indonesia, palm oil expansion has been even greater; by 2005 Indonesia had overtaken Malaysia in terms of mature oil palm areas. Globally, oil palm area has more than doubled, rising from 3.77 Mha in 1990 to 9.42 Mha in 20064.

Despite increases in the area under oil palm cultivation in Indonesia, table 6 shows that average yields remain higher in Malaysia. One reason for the lower yields may be the younger age of the Indonesia palms, which are not yet fully mature [205].

**Table 20.6 Average palm oil yields (tonnes of CPO per mature hectare)**

<table>
<thead>
<tr>
<th>Year</th>
<th>1990</th>
<th>1995</th>
<th>2000</th>
<th>2005</th>
</tr>
</thead>
<tbody>
<tr>
<td>Indonesia</td>
<td>3.09</td>
<td>3.43</td>
<td>2.86</td>
<td>3.58</td>
</tr>
<tr>
<td>Malaysia</td>
<td>3.67</td>
<td>3.46</td>
<td>3.57</td>
<td>4.18</td>
</tr>
<tr>
<td>Rest of the world</td>
<td>1.67</td>
<td>2.05</td>
<td>2.64</td>
<td>2.48</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>2.87</strong></td>
<td><strong>3.05</strong></td>
<td><strong>3.11</strong></td>
<td><strong>3.59</strong></td>
</tr>
</tbody>
</table>

Source: [205]

**20.3.2 Why has palm oil emerged as the leading vegetable oil?**

Over the past few decades, palm oil has emerged as the world’s leading vegetable oil in terms of both production and trade. According to Thoenes [206], there are several factors that explain this growth. Firstly, yields from plantations of oil palm far exceed yields from other oilseed crops such as rapeseed, soy and sunflower oil (see table 3). The average mature oil palm plantation produces just under 4 tonnes per hectare per year, about 10 times the yield of soybean oil and 2.4 times greater than rapeseed [197]. In contrast to other oilseed crops, which are annuals and must be replanted each year, oil palm bears fruit throughout the year and each tree lasts for 25 to 30 years [203]. In theory, oil palm yields could be doubled by improvements to the way the crop is managed and harvested, and high yielding cultivars could be introduced. However, as stated by Casson et al.[207] much of the world has yet to achieve this level of efficiency, and over the past decade there has been relatively little success in achieving increases in yield on oil palm plantations [203].

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Secondly, when compared other oilseed crops, oil palm has the lowest per unit production costs; soybean, the oilcrop with the next lowest production costs, has 20 percent higher costs [205]. The low cost production of palm oil has traditionally been dependent on access to cheap labour and land. As competition for both increases in Malaysia, companies are increasingly looking towards other SE Asian countries, and in particular Indonesia, for the expansion of oil palm, where land and labour pose fewer constraints on its development.

Thirdly, the oil palm is more energy efficient than other oilseed crops, using fewer inputs, such as agrochemicals and fuel for machinery, to produce one tonne of oil. Oil palm has an input to output ratio of 9.6, compared to rapeseed with a ratio of 3.0 and soybean with a ratio of 2.4 [196, 208].

Finally, the palm oil industry has benefitted from a favourable economic and policy environment, due to concerted efforts by government to develop the sector [206]. The palm oil market is also highly concentrated, with two countries controlling the vast majority of global production and trade. This concentration, argues Thoenes (ibid: 2), ‘has facilitated the control, continuous advancement and modernisation of production, trade and technological development’.

**20.3.3 Future supply**

Despite these positive aspects, it is expected that future growth and competitiveness of the oil palm industry is likely to be constrained by a number of factors. Palm oil yields have only increased marginally over the past 20 years [203]. As land becomes increasingly scarce and tighter environmental restrictions are imposed on the establishment of new plantations, yields will need to increase to meet future demand.

Oil palm plantations are characterised by relatively weak labour productivity, and due to the difficulties in mechanising plantations are also labour intensive. As a result, labour costs remain a significant component of production costs [206]. This is of particular concern in Malaysia, where labour shortages are leading to increased wages and therefore rising production costs. Increasing concern about the environmental and social sustainability of oil palm plantations has also had an impact on the production and trade of palm oil. Other issues include dependence on export markets, vulnerability to weather changes and concentration of the agricultural sector (ibid). In the longer term, Malaysia and Indonesia should expect to face increasing competition from emerging producers, including East and West Africa, and South and Central America. However, despite these limitations if past trends continue, global production of palm oil is expected to increase by 20 million tonnes to reach 54 million tonnes by 2012 [205].

**20.3.4 Production of biodiesel from palm oil**

Palm oil has been proposed as an ideal feedstock for biodiesel due to its high yields and low production costs; in the absence of subsidies, palm oil is the most competitive vegetable oil. However, table 20.7 demonstrates that to date the use of palm oil as a biodiesel feedstock has been fairly small compared to that of other vegetable oils.
Table 20.7 Percentage of biodiesel produced worldwide from various vegetable oils, 2006

<table>
<thead>
<tr>
<th>Source of biodiesel</th>
<th>Percentage (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rapeseed oil</td>
<td>84</td>
</tr>
<tr>
<td>Sunflower oil</td>
<td>13</td>
</tr>
<tr>
<td>Palm oil</td>
<td>1</td>
</tr>
<tr>
<td>Soybean oil and others</td>
<td>2</td>
</tr>
</tbody>
</table>

Source: [206]

Nonetheless, some Asian countries have already begun commercial production of biodiesel from palm oil. Currently, the majority of palm biodiesel produced in these countries is sold on the domestic market, where it competes with conventional diesel without subsidies [206]. Biodiesel production capacity is expected to increase rapidly over the next few years in Asia, with much of the commodity destined for export. The Malaysian and Indonesian governments have announced an official target to allocate 6 million tonnes of palm oil per year to biodiesel production; equivalent to around 40 percent of crude palm oil production (ibid).

In Malaysia, the government’s National Biofuel Policy has mandated the use of B5, or Envdiesel, which blends 5 percent processed palm oil with 95 percent conventional diesel [196]. Research is currently underway in Malaysia to produce a palm oil biodiesel blend that would meet EU standards. Sumathi et al [197], estimate that blending 5 percent palm oil with available diesel would create demand for an additional 260,000 tonnes of palm oil. Since 2006, the Malaysian government has approved 20 biodiesel projects with investments of $515 million; diverting more than 3 million tonnes of palm oil away from traditional markets [203]. Ironically, the Malaysian biodiesel programme has been instigated just as supplies of palm oil in the country are moving from surplus to deficit [209].

On a more cautionary note, Murphy [203] argues that diverting palm oil from traditional markets, including the food and oleochemical industries, to biodiesel will reduce stocks and increase prices for edible oil for relatively poor Asian consumers. Current demand for palm oil is largely driven by Asian markets requiring edible oils for their increasingly affluent populations; this demand is supplemented by largely European markets for non-edible oils (ibid). Recent demand for palm oil as a biodiesel feedstock in Europe has distorted the palm oil markets, leading to impacts on the price of edible oils in general. In recognition of growing concerns over the use of palm oil for food versus fuel, in 2006 the Malaysian government suspended new manufacturing licences to build biodiesel plants. While some authors (see for example Murphy, [203] argue that the use of palm oil as a biofuel feedstock is a waste of a valuable commodity, others (such as Basiron, [199] argue that the industry has the capacity to cope with both growing demand for food and for fuel. Murphy [203] concludes that ‘it seems unlikely that it will make economic sense to burn a potentially valuable semi-refined product that can serve either as a nutritious food or as a source of useful oleochemicals’.

### 20.4 Economics

In 2006, palm oil and palm kernel oil were the most traded oils in the global oils and fats industry, with a combined market share of 56 percent [201]. World consumption of palm oil comes second only to soy oil and amounted to 31.5m tonnes annually [194]. Two key reasons underlie the current positioning of palm oil: firstly, it has
lower production costs than other oils and fats (with average production costs around $100 per tonne lower than major alternatives); and secondly that it commands lower prices than alternative oils and fats [205].

Palm oil is competitively priced due to a guaranteed and consistent supply, although as a low value commodity in international markets that are often fully supplied with oil, this may have acted as a disincentive to innovation in yields [203]. Between 1950 and 2002 there was a long term, steady decline in the price of palm oil. However, since 2003, the price of palm oil has increased as demand has grown, and demand for biodiesel has been a major influence on these recent price increases. Yet despite this increased demand, palm oil remains the lowest priced vegetable oil [206].

Demand for palm oil is largely driven by Asian markets, primarily India (14%), Indonesia (11%), China (9%), Malaysia (6%) and Pakistan (6%); the EU accounts for 12% of global demand [196, 207]. Demand from the EU has remained relatively stable over the past few decades while demand from Asian countries has risen sharply. Despite being the world’s biggest producer of palm oil, domestic consumption of palm oil and palm kernel oil is relatively low in Malaysia. As a result, Malaysia exports most of its PO and has the biggest market share in the global vegetable oils and fats export trade at 28 percent (or 15.6 million tonnes out of a global total of 56 million tonnes); Indonesia has the second largest market share at 24.5 percent [196]. Murphy [203] highlights the importance of palm oil to the Malaysian economy, which is worth an annual US$4 billion out of a total GNP of $60 billion.

20.4.1 The provision of employment oil palm estates

According to Basiron [199] a typical oil palm estate in Malaysia will cover more than 2,000 hectares to take advantage of economies of scale. An estate of this size would employ a manager, three assistant managers, and nine field staff. Due to the difficulties in mechanising plantations, estates also employ manual workers to carry out various tasks such as weeding, application of fertilisers and harvesting. The Malaysian oil palm industry is also attracting a growing number of smallholders. To provide support to smallholders and capitalise on economies of scale, the Federal Land Development Agency (FELDA) was established in 1956 [196, 199, 201]. The oil palm industry is one of Malaysia’s biggest employers, providing direct and indirect employment to around 860,000 people [196, 201]. The oil palm industry is also an important employer in Indonesia with more than 800,000 people employed directly, and an estimated 2 million people employed indirectly [210].

20.5 Environmental and ecological impacts

Much of the recent debate on biofuels has focused on the environmental and social sustainability of potential biofuel feedstocks, and oil palm in particular has been subject to widespread criticism from NGOs and academics. Yet the cultivation of oil palm is not inherently damaging; indeed it has been cultivated sustainably in Africa for millennia. Nonetheless, forests are being cleared to make way for oil palm plantations, leading to the loss of biodiversity and ecosystem services; oil palm expansion has been cited as the primary driver of deforestation in Malaysia and Indonesia [211].
20.5.1 Expansion of palm oil

South East Asia has long been attractive to developers of oil palm for a number of reasons including, a favourable climate, comparatively low labour costs and land rents, concerted plans by government to develop the sector, provision of attractive legal frameworks, and the provision of cheap loans and other fiscal incentives for developers [212]. Peninsular Malaysia has traditionally been the focus of oil palm expansion; however, the rising costs of labour and land in peninsular Malaysia has led developers to look elsewhere to expand the cultivation of oil palm. Sabah and Sarawak (Malaysian Borneo), Thailand, Cambodia, Papua New Guinea, and the Solomon Islands all offer potential, but most expansion is currently underway in Indonesia.

The variance in the scale of planned expansion can be illustrated using the examples of Thailand and Indonesia. In Thailand between 2003 and 2004, oil palm plantations increased by around 4 percent to cover 300,000 hectares. There are currently plans underway to plant oil palm at a rate of 64,000 hectares per year to reach a target of 1.6 Mha by 2030 [212]. By comparison, Indonesia currently has an estimated 6Mha under cultivation of oil palm. The Department for Agriculture argues that there is a further 27Mha of ‘unproductive forestland’ (i.e. degraded forests) which could be planted with oil palm. While central government has ambitious plans to plant a further 4Mha by 2015, dedicated to biofuel production, regional governments have proposed an even more ambitious 20Mha for oil palm development, 80 percent of which will occur in Sumatra and Kalimantan [212, 213]. Several questions arise from these figures: where will this additional land come from? What will be the environmental and social impacts of planting the land with oil palm? And who are the potential winners and losers in this development? These are not easy questions to answer.

20.5.2 Deforestation and land use change

Much oil palm expansion has occurred in primary forests and other biodiversity rich ecosystems. Primary forests in SE Asia are under pressure from logging and for conversion to other uses, particularly oil palm. Wakker [202] comments that it is not easy to establish the role that oil palm expansion plays in deforestation and uses industry figures to provide some insights. In 2004, the Indonesian Palm Oil Research Institute (IPORI) estimated that 3 percent of all oil palms in Indonesia had been established in primary forest and 63 percent in secondary forest and bush. In Malaysia, the Malaysian Palm Oil Association (MPOA) calculated that 66 percent of plantations had been converted from other agricultural uses, and the remainder established in logged-over forest land. From these figures Wakker (ibid: 16) estimated that 3.26Mha had been cleared of forests in Indonesia and Malaysia, and that 48 percent of existing plantations had involved forest conversion.

In Malaysia, the acreage of oil palm doubled between 1990 and 2005; the majority of which involved the substitution of agricultural crops with lower market values, such as cocoa and rubber, with oil palm. Table 20.8 shows the change in agricultural land use between 1990 and 2005.
Table 20.8  Changes in land use of selected crops in Malaysia (million hectares), 1990 to 2005

<table>
<thead>
<tr>
<th>Crop</th>
<th>Year 1990</th>
<th>2005</th>
<th>Change</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oil palm</td>
<td>1.98</td>
<td>4.05</td>
<td>2.07</td>
</tr>
<tr>
<td>Rubber</td>
<td>1.82</td>
<td>1.25</td>
<td>-0.57</td>
</tr>
<tr>
<td>Cocoa</td>
<td>0.42</td>
<td>0.03</td>
<td>-0.39</td>
</tr>
<tr>
<td>Coconut</td>
<td>0.32</td>
<td>0.13</td>
<td>-0.19</td>
</tr>
<tr>
<td>Total</td>
<td>4.54</td>
<td>5.46</td>
<td>0.93</td>
</tr>
</tbody>
</table>

Source: [208]

Over this time period, the acreage of other agricultural crops fell by 1.15Mha, of which a large proportion was converted to oil palm production [214]. However, despite this the total land area under cultivation increased by 0.93Mha, and it is likely that much of this expansion involved forest conversion. Indeed, Wakker [202] attributed 87 percent of deforestation in Malaysia between 1985 and 2000 to the development of oil palm estates.

The Malaysian oil palm industry has a strong and active lobby that strenuously denies any statement that Malaysian palm oil causes negative environmental or social impacts. It frequent cites laws that govern the plantation and management of oil palm estates and its membership of the Roundtable on Sustainable Palm Oil (RSPO) as evidence that Malaysian palm oil is sustainable. However, while the cultivation of oil palm in Malaysia may be more sustainable than it has traditionally been, there is evidence that oil palm expansion is still causing deforestation and habitat loss [215]. Indeed, the UK Advertising Standards Authority (ASA) recently upheld a complaint by Friends of the Earth against an advert by the Malaysian Palm Oil Council (MPOC) that described palm oil as ‘sustainably produced’. Furthermore, while the expansion and production of oil palm in Malaysia incorporates sustainability standards, there is no such obligation for Malaysian firms to behave responsibly elsewhere.

In Indonesia despite the clearance of more than 28 Mha of forest, largely for land conversion, only one third of the land cleared has been planted with oil palm [216]. Some NGOs have alleged that obtaining permits to convert forest into plantations is often nothing more than a ploy to gain access to the timber [212]. The standing timber in a forest is highly valuable, yielding up to $2,100 per hectare, and provides a useful source of income for developers who may use these proceeds either to cover the costs of starting up a plantation, which may take up to 5 years to establish, or who may simply abandon the project once the timber has been harvested [202, 212]. In 2001, the World Bank estimated that around 40 percent of Indonesia’s legal timber supply had been harvested from land clearance for plantations (cited in Colchester et al., [212]).

In addition to the concerns that oil palm expansion plays in deforestation, it is also leading to the conversion of other habitats including the carbon-rich peatlands of SE Asia. SE Asia has 27.1Mha of peatlands, which represents 6 percent of the global total. Indonesia alone has a total of 22.5Mha of peatlands, equivalent to 12 percent of the archipelago’s land area [208]. Traditionally, these peatlands have been inaccessible to agriculturalists because of their damp and infertile soils. Drainage, however, renders these soils suitable for agriculture, and much of today’s oil palm expansion is occurring on drained peatlands [213]. The loss of peatlands is a major cause for concern due to the huge amounts of CO$_2$ that are released when peatlands

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are drained. Drainage also increases the risk of fire, and CO$_2$ released from peatland fire is thought to have contributed twice as much CO$_2$ as that emitted through drainage. Greenpeace (ibid: 2) estimate that emissions of greenhouse gases from peatlands are ‘set to rise by at least 50 percent by 2030 if predicted expansion proceeds’. In addition to the net loss of carbon from peatlands, there are also widespread concerns about the loss of carbon stock arising from deforestation. Carbon storage in above-ground biomass in tropical forests is around 10 times greater than that of oil palm plantations [37, 217]. Therefore, the conversion of tropical forests to plantations results in a net loss carbon to the atmosphere, greatly reducing the greenhouse gas benefits associated with the use of palm oil for biodiesel. The use of fire during forest clearance and preparation of the site will also lead to the emissions of carbon from the soil, although the amount lost will depend on intensity of the fire, soil type and slope [217].

### 20.5.3 Biodiversity loss

The loss of forests and other ecosystems has also had negative impacts on biodiversity, and in particular there are concerns for umbrella species such as orang-utan, Sumatran tiger, and rhinoceros. Research carried out by Koh and Gan (cited in [208]) concluded that, despite concerns that oil palm plantations have low biodiversity, large populations of birds, butterflies and mammals were recorded, and rare species such as the leopard cat were observed. However, while this research demonstrates that plantations can provide suitable habitats for some species, it provides no indication of species diversity. Other research estimates that oil palm plantations support between 0 and 20 percent of the biodiversity found in rainforests [202]. When oil palm expansion takes place in biodiversity rich areas, such as much of the tropical forest earmarked for plantations in Kalimantan, Sumatra and Borneo, biodiversity losses will inevitably occur.

Of particular concern to many NGOs is the loss of suitable orang-utan habitat in Borneo and Sumatra. A report by Nelleman et al., [211] highlighted the rapid expansion in oil palm plantation acreage, calling it ‘one of the greatest threats to orang-utans and the forests in which they live’. Habitat loss leads to further impacts on orang-utan populations as infrastructure is developed, opening up further tracts of previously undisturbed forest and increasing access for hunters and poachers. Conflicts between humans and orang-utans also created as the apes stray onto plantations in search of food where they may be killed for meat or to protect the crops, or sold into the illegal pet trade [211, 216].

### 20.5.4 Mitigating the environmental impacts

To a certain extent some of the environmental impacts of oil palm expansion can be mitigated through the use of best management practices (BMPs). Examples of BMPs that are encouraged in oil palm plantations include Integrated Pest Management (IPM), which minimises the use of agrochemicals and promotes the use of biological controls, such as barn owls and parasitoids. Intercropping with legumes also reduces the need for fertilisers, decreases soil erosion and runoff; contouring hilly slopes also helps to minimise soil erosion. In the 1990s, the Malaysian government implemented a ‘zero-burn’ policy, prohibiting the burning of old palms; today, these are left to decompose in situ, recycling 90 to 100 tonnes of organic matter per hectare [196]. However, this policy has contributed to an increase in the incidence of pests and diseases, which are able to persist in the rotting debris [203] the impacts of
deforestation on carbon balances may also to some extent be mitigated by the plantation of oil palms. A study of the capacity of oil palm plantations to act as carbon sinks showed that the net assimilation from oil palms was 64.5 tonnes of CO$_2$ per hectare per year, while that of rainforests was 42.4 of CO$_2$ per hectare per year, shown in table 20.9 (Henson, 1999 cited in [196] and [208]. The same study also reported that an oil palm plantation assimilates up to 36.5 tonnes of dry matter per year, compared to rainforests which assimilate 25.7 tonnes. This research therefore suggests that plantations may be more efficient than rainforests at assimilating CO$_2$.

### Table 20.9. Physiological parameters of oil palm and rainforest

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Oil palm plantation</th>
<th>Rainforest</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gross assimilation (t CO2/ ha/ yr)</td>
<td>161</td>
<td>163.5</td>
</tr>
<tr>
<td>Total respiration (t CO2/ ha/ yr)</td>
<td>96.5</td>
<td>121.1</td>
</tr>
<tr>
<td>Net assimilation (t CO2/ ha/ yr)</td>
<td>64.5</td>
<td>42.4</td>
</tr>
<tr>
<td>Lear area index</td>
<td>5.6</td>
<td>7.3</td>
</tr>
<tr>
<td>Photosynthetic efficiency (%)</td>
<td>3.18</td>
<td>1.73</td>
</tr>
<tr>
<td>Radiation conversion efficiency (g/ m)</td>
<td>1.68</td>
<td>0.86</td>
</tr>
<tr>
<td>Standing biomass (t/ ha)</td>
<td>100</td>
<td>431</td>
</tr>
<tr>
<td>Biomass increment (t/ yr)</td>
<td>8.3</td>
<td>5.8</td>
</tr>
<tr>
<td>Dry mass productivity (t/ yr)</td>
<td>36.5</td>
<td>25.7</td>
</tr>
</tbody>
</table>

Sources: [196, 208]

However, these results should be treated with caution. It may be that the plantations studied were young and therefore growing quickly; the assimilation rate would be expected to decline as the plantation matured. The total carbon stock of plantations will also be lower than that of tropical forests, which with more extensive root systems (because they are taller and more mature) would keep CO$_2$ out of atmospheric circulation. Thus, the assimilation of CO$_2$ by oil palm plantations is only one part of a more complex picture.

## 20.6 Social context

If managed well, oil palm has the potential to provide a useful source of food and income for local communities. Problems arise, however, when plantations are imposed on people’s lives and lands with little respect for human rights and customary laws. When imposed without due consideration of the local context, oil palm can lead to negative social impacts on previously self-sufficient communities, including loss of livelihood, land alienation and conflict [212]. Plantations may bring employment opportunities to communities but questions have been raised about the fairness of such systems, which can lock small plantation owners into exploitative working conditions [212]. Rising awareness of the negative social impacts and exploitation of customary laws has led to increasing opposition to proposed oil palm plantations.

More than 60 million people in Indonesia are dependent on forests for their livelihoods, and of these a large percentage are indigenous peoples. Protection is provided to indigenous peoples and local communities by the Indonesian Constitution, which recognises the existence of customary law communities, their right to self-governance and traditional land rights. Conversely, the Indonesian Constitution also recognises the right of the state to control and allocate natural resources for the benefit of the Indonesian people. This contradiction means that
customary laws are only weakly respected, are frequently subordinated to the national interest and powerful private sector interests and that forest conversion is favoured over conservation in order to increase revenue [212]. Decentralisation laws were introduced between 1998 and 2002, which attempted to address some of these issues by encouraging greater participation in decision making. However, FoE et al [216] argue that decentralisation has sped up the process of allocating permits and can be linked to an observed increase in deforestation rates. The issue is further complicated by regional variation in the acceptance and recognition of customary laws [212].

Research by Colchester et al [212] provides substantial evidence that land for oil palm developments has all too often been acquired by dubious means. The study concludes that the failure of developers to adhere to legal requirements is as much due to weak institutional capacity as it was to dishonest oil palm companies. As a result the oil palm industry is the most conflict ridden in Indonesia, and between 1998 and 2002 479 people were harmed in conflicts relating to oil palm development and land tenure [216].

The situation appears to be less divisive in Malaysia, where the oil palm industry is better established. The Malaysian Palm Oil Council [196] asserts that the industry is a major driver of economic growth, providing jobs for rural people and supporting national development. MPOC argues that plantations act as focal points for rural communities and provide not only employment but access to housing, clean water, electricity, communications, health services and education (ibid). In 1956, the Federal Land Development Authority (FELDA) was established in Malaysia to alleviate rural poverty through the ‘resettlement of landless farmers in land development schemes where they plant economically viable crops’ [199]. Each family is provided with four hectares of land to be cultivated with oil palm, rubber or cocoa; these smallholdings are aggregated into larger estates to capitalise on economies of scale. FELDA also develops infrastructure and provides managerial services, which enable farmers to work towards ownership of the land. By 2007, the scheme had provided assistance to more than 100,000 settlers and their families. FELDA is also the world’s single largest plantation company, covering more than 600,000 hectares, and has an annual revenue of US$2 billion. FELDA has also been recognised by other countries as a model for poverty reduction [199, 203]. However, despite schemes such as FELDA, and protestations by the Malaysian oil palm industry that it is socially benign, there have been demonstrations by plantation workers and communities protesting against weak housing rights, low wages and land right conflicts on plantations [218].

Finally, there are also concerns about the use of agrochemicals on oil palm plantations, which have negatively impacted on human and ecosystem health. A lack of health and safety procedures governing the use of agrochemicals has led to human intoxication and contamination of the land surrounding plantations [216].

20.6.1 Roundtable on Sustainable Palm Oil

In recent years, the palm oil industry has been facing growing criticism from NGOs, communities and consumer groups as awareness grows about the negative environmental and social impacts of oil palm cultivation. As a result, industry and policymakers have come under increasing pressure to address these issues, which led to the establishment of the Roundtable on Sustainable Palm Oil (RSPO) in 2002. As of January 2008, the RSPO had 283 members, including some of the world’s biggest
corporations such as Unilever (also President of the organisation), Cargill and Nestlé [219].

The RSPO aims to: research and develop definitions and criteria for sustainable palm oil production and use; to facilitate the implementation of sustainable best practices; and to promote cooperation within the supply chain (ibid). It aims to achieve these aims through eight principles:

1. A commitment to transparency
2. Compliance with applicable laws and regulations
3. A commitment to long term economic and financial viability
4. The use of appropriate best practice by growers and millers
5. Environmental responsibility and conservation of natural resources and biodiversity
6. The responsible consideration of employees and of individuals and communities affected by growers and mills
7. The responsible development of new plantings
8. A commitment to continuous improvement in key areas of activity

Under each of these principles are a number of criteria that were developed with stakeholder input, and members of the RSPO are obliged to report on their progress in meeting these criteria [208, 219]. However, in a critique of the initiative, Greenpeace [213] questioned the impact that the RSPO has had in terms of reducing oil palm expansion into forests and other habitats, going so far as to call it ‘negligible’. One of their biggest criticisms is that despite efforts to improve transparency ‘there is no system to segregate palm oil that meets RSPO criteria from palm oil coming from deforestation’ (ibid: 34). The entire supply chain from production to refining and blending, and from distribution to trade, is controlled by a few companies, and as a result it is virtually impossible to trace the source of the palm oil and therefore to promote responsible purchasing. Many of those who control the supply chain are also members of the RSPO. Ellsmore [220] adds that because there is no Material Identity Card (MIC) scheme in place to trace the raw material from its origins and through the refining processes, it is impossible to know exactly which company or supplier has purchased the oil from and therefore, which plantations the oil has originated from.

20.7 Constraints

The past 20 years have seen only marginal increases in yields of palm oil, and growth in production has been due to rapid expansion of plantations rather than due to yield increases. It is this stagnating yield that represents the key technical constraint on the availability of palm oil as a feedstock for biodiesel. As the availability of land declines and increasingly stringent environmental restrictions are imposed on the establishment of new plantations, yields will need to increase to keep up with demand. Technical improvements in crop management and the use of high yielding cultivars may reduce this constraint. Competition with the food and oleochemical markets will also constrain availability, and increasing demand for palm oil in Asian
markets mean this is likely to remain a constraint for the foreseeable. Awareness about the negative social and environmental impacts of oil palm plantations may also constraint the social acceptability of this feedstock.

20.8 Conclusions

There is currently much debate surrounding oil palm, and awareness is increasing of the negative sustainability impacts associated with its cultivation. The expansion of oil palm has been named as a key driver of deforestation and peatland destruction in Malaysia and Indonesia, and represents a major threat to the endangered orang-utan and to the livelihoods of many communities and indigenous peoples who are dependent on forests for their survival. However, oil palm does have the potential to provide a source of sustainably produced oil, due to the crop’s high, energy efficient yields and potential as a source of food and income for communities.

Current demand for palm oil is driven largely by increasingly affluent Asian markets, and in particular India and China, and their increasing consumption of oils and fats. Recent demand for palm oil as a biodiesel feedstock has led to distortions in the market and has increased the price of edible oils in general. This demand for biofuels has introduced an ethical component to the debate, as stocks of palm oil are diverted from relatively poor Asian consumers to supply biodiesel to Europeans. Ultimately, whether it makes economic sense to use of palm oil as a food source or as a feedstock for biodiesel will depend on the policy decisions taken by the international community, and in particular the EU.
21. Palm Kernel Expeller

The previous chapter focused on the use of palm oils (CPO and PKO) as a feedstock for biofuels and the sustainability concerns associated with their production. This review looks at one of the by-products of PKO production, Palm Kernel Expeller (PKE). Because many of the issues, such as environmental and social concerns, relating to the production of PKE are those associated with the production of palm oils, they will not be reviewed here except where relevant. This review therefore focuses on the production and economics of this by-product.

21.1 Feedstock description

Palm Kernel Expeller (PKE), also referred to as Palm Kernel Cake, is an important by-product in the production of Palm Kernel Oil (PKO). PKE is high in fibre, protein and lignocellulose, and as a result has traditionally been used in the formulation of animal feed, particularly cattle.

A second emerging international market for PKE, and other oil palm by-products, is as a biomass feedstock providing an alternative to coal. Traditionally the by-products of palm oil processing, such as the fibres and shells, have been used in situ to generate steam and electricity for the milling process; the empty fruit bunches (EFBs) are also used recycled, being used as fertilisers in plantations wherever possible. A further use for PKE and other by-products that is currently the subject of research activity, particularly by the Malaysian palm oil industry, is as a feedstock for the production of second generation biofuels.

21.2 Production

Oil palm is a multi-product crop; in addition to the primary products crude palm oil (CPO) and palm kernel oil (PKO), plantations generate a large quantity of cellulosic biomass such as fibres from the trunk and fronds. These by-products have a number of different uses and can be processed to produce products such as bioplastics, plywood and animal feed.

The milling process also produces a number of by-products, one of which is Palm Kernel Expeller (PKE). Using mechanical processes PKE is obtained during the extraction of PKO; illustrated in figure 1. After the palm kernels are cleaned, they are ground and screw pressed; an intermediary flaking and conditioning stage may also take place. During the screw processing, the raw PKO is separated and diverted for clarification while the PKE is cooled and stored [221].
Figure 1. Mechanical extraction and processing of palm kernel oil

Unlike other annual oilseed crops oil palm is a perennial crop and fruits throughout the year, providing a year round supply of palm oils and PKE. However, monthly variation in yields means that producers are unable to guarantee a constant and consistent supply of biomass [221].

One hectare of oil palm typically produces around 4 tonnes of crude palm oil and 0.4 tonnes of PKE per year [205, 222]. Malaysia is the largest producer and exporter of PKE; in 2005 producing 2.10 million tonnes of PKE [201]. In 2007, the amount of PKE exported by Malaysia was greater than that produced; in the first half of the year, production of PKE was 962,000 tonnes while exports totalled more than 985,000 tonnes [223]. Future production of palm oil is expected to reach 45.9 million tonnes by 2015, this would also significantly increase the amount of available PKE, which would reach an estimated 4.59 million tonnes [222].

21.3 Economics

The recent development of a second market for PKE has led to the emergence of a ‘floor price’, which has decreased the threat of a price collapse [223]. Trade in PKE has also been affected by increased demand for biofuels, particularly demand for maize, and prices of PKE have increased dramatically. In 2007, PKE was trading at $120 per tonne, more than double the price in 2006. Despite these price increases, PKE remains cheaper than feed alternatives. The increased price of PKE has led to a slowdown in demand for PKE as a biomass feedstock, as it becomes too expensive as
an alternative to coal. In the long run prices are unlikely to continue to rise as demand slows and the production of grain increases (ibid).

21.4 Applications
Although the main use of PKE is as an agricultural commodity, it is increasingly being used as a fuel source. It is attractive as an energy feedstock because it has a high net calorific value\(^6\) and ‘can be co-milled and combusted directly with coal in the main boiler of a power station’ [224]. In 2005, 30 percent\(^7\) of co-firing feedstocks in coal-fired power stations were derived from oil palm products [225]. The existence of other markets for PKE, such as in animal feed and as an energy feedstock in the milling process, may limit its availability as an energy feedstock. However, increased demand for biofuels is expected to increase the production of palm oil, which would lead to increased availability of PKE. Although increased availability of PKE would lead to lower prices, whether this would in turn lead to increased use in co-firing will also depend on policy and regulatory frameworks [224].

21.5 Environmental issues
The main sustainability issues associated with the production of PKE have already been discussed in review 9 (oil palm) and will not be discussed again here. However, a specific environmental consideration is the emissions arising from its use and transportation. As a residue or by-product of palm kernel production it could be argued that the only emissions that need to be attributed to its use are the non-CO2 emissions arising from combustion and those emissions arising from the long-distance transportation of the biomass [222, 225].

21.6 Constraints
While some of the constraints on the use of PKE as a bioenergy feedstock will be the same as for oil palm, including the marginal success in increasing yields and the labour intensity of plantations, others are specific to PKE. In particular, the existence of other markets for this product may limit its availability. Recent sharp increases in the price of PKE may also constrain its use as a feedstock.

\[^6\] The energy density of PKE varies between 14 to 17 MJ/kg depending on the moisture content
\[^7\] 449,657 tonnes out of a total 1,412,122 tonnes
22. Soya

22.1 Feedstock description

Soybean (Glycine max) is one of the world’s most important sources of edible oil and high-quality plant protein for both humans and animals [226, 227]. Together protein and oil account for up to 60 percent of dry soybeans by weight; accounting for 40 percent and 20 percent respectively. In addition, soy protein contains all the amino acids that are essential for human health, and have a greater resemblance to animal protein than other vegetable proteins [228]. Zhang [27] estimates that there are more than 12,000 products based on the soybean, including tofu, soy sauce, soy oil, biodiesel, paints, detergents and candles.

The majority of the soybean crop is solvent-extracted for vegetable oil while the by-product, defatted soy meal, is used for animal feed. Only a small percentage of the crop is directly consumed. Soybean is cultivated in a number of countries, but production is dominated by the United States, Brazil, Argentina and China.

There have been more than 350 oil-bearing crops identified, although only a handful have been considered as potential alternatives for diesel, these include soybean, palm, sunflower and rapeseed [147]. Soy oil is the world’s most important vegetable oil, commanding around 30 percent of the global market share; however it is slowly losing this market to palm oil [207]. Table 22.1 shows the world consumption of vegetable and marine oil between 1998 and 2003.

Table 22.1 World vegetable and marine oil consumption (million metric ton).

<table>
<thead>
<tr>
<th></th>
<th>1998</th>
<th>1999</th>
<th>2000</th>
<th>2001</th>
<th>2002</th>
<th>2003</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soybean</td>
<td>23.5</td>
<td>24.5</td>
<td>26.0</td>
<td>26.6</td>
<td>27.2</td>
<td>27.9</td>
</tr>
<tr>
<td>Palm</td>
<td>18.5</td>
<td>21.2</td>
<td>23.5</td>
<td>24.8</td>
<td>26.3</td>
<td>27.8</td>
</tr>
<tr>
<td>Rapeseed</td>
<td>12.5</td>
<td>13.3</td>
<td>13.1</td>
<td>12.8</td>
<td>12.5</td>
<td>12.1</td>
</tr>
<tr>
<td>Sunflower seed</td>
<td>9.2</td>
<td>9.5</td>
<td>8.6</td>
<td>8.4</td>
<td>8.2</td>
<td>8.0</td>
</tr>
<tr>
<td>Peanut</td>
<td>4.5</td>
<td>4.3</td>
<td>4.2</td>
<td>4.7</td>
<td>5.3</td>
<td>5.8</td>
</tr>
<tr>
<td>Cottonseed</td>
<td>3.7</td>
<td>3.7</td>
<td>3.6</td>
<td>4.0</td>
<td>4.4</td>
<td>4.9</td>
</tr>
<tr>
<td>Coconut</td>
<td>3.2</td>
<td>3.2</td>
<td>3.3</td>
<td>3.5</td>
<td>3.7</td>
<td>3.9</td>
</tr>
<tr>
<td>Palm kernel</td>
<td>2.3</td>
<td>2.6</td>
<td>2.7</td>
<td>3.1</td>
<td>3.5</td>
<td>3.7</td>
</tr>
<tr>
<td>Olive</td>
<td>2.2</td>
<td>2.4</td>
<td>2.5</td>
<td>2.6</td>
<td>2.7</td>
<td>2.8</td>
</tr>
<tr>
<td>Fish</td>
<td>1.2</td>
<td>1.2</td>
<td>1.2</td>
<td>1.3</td>
<td>1.3</td>
<td>1.4</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>80.8</strong></td>
<td><strong>85.9</strong></td>
<td><strong>88.7</strong></td>
<td><strong>91.8</strong></td>
<td><strong>95.1</strong></td>
<td><strong>98.3</strong></td>
</tr>
</tbody>
</table>

*From: [194]*

This paper reviews the origin, production and economics of soy, before considering the specific environmental and social sustainability concerns. It focuses on soy from Latin America, principally because most of the predicted soy expansion is expected to occur in biodiverse Latin American countries, in particular Brazil and Argentina. The expansion of soy in less biodiversity rich countries such as the United States, China and India has fewer sustainability impacts [207].
22.2 Feedstock origin

Soybean is originally from mainland China, and has been an important food plant in Asia for more than 6,000 years. It was introduced to Europe in the 18th century, to America late in the 19th century, and into South America by Japanese migrants in the early 20th century [228, 229]. Having originated in the mid-latitudes, soybeans are now expanding into tropical areas through the development of new varieties that are tolerant to the environmental conditions of these regions [227].

22.3 Production

Soybean (Glycine max) is an annual crop belonging to the Leguminosae family. Soybean is best suited to the relatively humid subtropics, although it may also be grown in temperate and tropical regions; it has a growing period of four to five months. Environmental conditions such as latitude, altitude, temperature and precipitation all affect seed composition, and in particular the protein and oil content [227]. The key requirements of soybeans are summarised in Table 22.2.

Table 22.2 Soybean crop requirements.

<table>
<thead>
<tr>
<th>Soil</th>
<th>Water</th>
<th>Nutrients</th>
<th>Climate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moist alluvial soils with good organic content, high water capacity, good structure, loose soil</td>
<td>High</td>
<td>Optimum soil pH of 6 to 6.5</td>
<td>Tropical, sub-tropical, temperate climates</td>
</tr>
</tbody>
</table>

(Source: [230])

Soybeans require at least moderate soil moisture in order to germinate and for seedlings to become established, although once established the plants are able to withstand short dry periods. In sub-tropical and tropical regions between 500 and 750mm of rainfall is necessary to obtain good yields [231]. Acidic soils (pH 6 - 6.5) are essential for the formation of nodules and nitrogen fixing bacteria, although some cultivars are able to survive in more acidic or alkaline soils.

Soybeans are sensitive to day length, the key factor affecting the amount of vegetative growth before flowering, and thus the timing of flowering. Most cultivars only flower when there is less than 14 hours of daylight, while very short days (12 hours or less) lead to premature blooming and thus reduced yields. Sensitivity to day length is one of the reasons that the cultivation of soybean is not possible in most parts of Europe [226, 231].

Soybeans require fertiliser, including the macronutrients phosphorous, potassium, calcium and magnesium; sometimes micronutrients may also be required. Rehm and Espig (2001 in [231]) calculated that the production of one tonne of seeds removes around 15kg of phosphorous and 50kg of potassium from the soil. As a member of the Leguminosae family, soybeans will not need nitrogen if the seeds have been properly inoculated with the nitrogen fixing bacteria, Rhizobium, or if soybean is regularly grown in rotation with other crops [226].
Control of weeds is essential during the first few weeks of crop establishment, which are removed mechanically or through herbicides. Soybean is vulnerable to several pests and diseases which can lead to reduced yields, although these may be controlled through the cultivation of resistant varieties, seed selection, sanitary measures and crop rotations [231]. Insecticides are often used against the leaf-eating beetle and soybean moth. The use of GM varieties of soybean will be discussed in more detail in section 5.3.

22.3.1. Global production of soybean

In 2005, the global average yield of soybean per hectare was 2.2 tonnes, but there were large differences between countries, with Italian farmers reporting the highest yields of 3.6 tonnes per hectare [232]. The average yields of the ten producer countries are shown in Table 22.3.

<table>
<thead>
<tr>
<th>Year (yield per hectare, kg/ha)</th>
<th>1990</th>
<th>1995</th>
<th>2000</th>
<th>2005</th>
</tr>
</thead>
<tbody>
<tr>
<td>Argentina</td>
<td>2,157</td>
<td>2,045</td>
<td>2,339</td>
<td>2,729</td>
</tr>
<tr>
<td>Bolivia</td>
<td>1,623</td>
<td>2,070</td>
<td>2,122</td>
<td>1,810</td>
</tr>
<tr>
<td>Brazil</td>
<td>1,732</td>
<td>2,200</td>
<td>2,400</td>
<td>2,230</td>
</tr>
<tr>
<td>Canada</td>
<td>2,610</td>
<td>2,783</td>
<td>2,548</td>
<td>2,704</td>
</tr>
<tr>
<td>China</td>
<td>1,455</td>
<td>1,662</td>
<td>1,656</td>
<td>1,751</td>
</tr>
<tr>
<td>India</td>
<td>1,015</td>
<td>1,012</td>
<td>822</td>
<td>908</td>
</tr>
<tr>
<td>Indonesia</td>
<td>1,115</td>
<td>1,137</td>
<td>1,234</td>
<td>1,305</td>
</tr>
<tr>
<td>Italy</td>
<td>3,359</td>
<td>3,753</td>
<td>3,576</td>
<td>3,630</td>
</tr>
<tr>
<td>Paraguay</td>
<td>1,994</td>
<td>3,008</td>
<td>2,533</td>
<td>2,024</td>
</tr>
<tr>
<td>US</td>
<td>2,292</td>
<td>2,376</td>
<td>2,561</td>
<td>2,839</td>
</tr>
<tr>
<td>Global average</td>
<td>1,935</td>
<td>2,204</td>
<td>2,179</td>
<td>2,193</td>
</tr>
</tbody>
</table>


The top four soybean producers, the USA, Brazil, Argentina and China, account for almost 90 percent of global yields. Table 22.4 lists the top ten producers of soybean, with the world total production.

<table>
<thead>
<tr>
<th>Year (million tonnes)</th>
<th>1990</th>
<th>1995</th>
<th>2000</th>
<th>2005</th>
</tr>
</thead>
<tbody>
<tr>
<td>Argentina</td>
<td>10.7</td>
<td>12.1</td>
<td>20.2</td>
<td>38.3</td>
</tr>
<tr>
<td>Bolivia</td>
<td>0.2</td>
<td>0.9</td>
<td>1.2</td>
<td>1.7</td>
</tr>
<tr>
<td>Brazil</td>
<td>19.9</td>
<td>25.7</td>
<td>32.7</td>
<td>51.2</td>
</tr>
<tr>
<td>Canada</td>
<td>1.3</td>
<td>2.3</td>
<td>2.7</td>
<td>3.2</td>
</tr>
<tr>
<td>China</td>
<td>11.0</td>
<td>13.5</td>
<td>15.4</td>
<td>16.8</td>
</tr>
<tr>
<td>India</td>
<td>2.6</td>
<td>5.1</td>
<td>5.3</td>
<td>6.9</td>
</tr>
<tr>
<td>Indonesia</td>
<td>1.5</td>
<td>1.7</td>
<td>1.0</td>
<td>0.8</td>
</tr>
<tr>
<td>Italy</td>
<td>1.8</td>
<td>0.7</td>
<td>0.9</td>
<td>0.6</td>
</tr>
<tr>
<td>Paraguay</td>
<td>1.8</td>
<td>2.2</td>
<td>3.0</td>
<td>4.0</td>
</tr>
<tr>
<td>USA</td>
<td>52.4</td>
<td>59.2</td>
<td>75.1</td>
<td>85.0</td>
</tr>
<tr>
<td>World total</td>
<td>108.2</td>
<td>127.0</td>
<td>161.4</td>
<td>214.8</td>
</tr>
</tbody>
</table>


In 1990, the US accounted for almost 50 percent of the world total production of soybean, but by 2005 this share had fallen to less than 40 percent. The proportion of
Brazilian and Argentinean soybean increased between 1990 and 2005 by 6 percent and 8 percent respectively [232]. By 2010, Brazil and Argentina are expected to surpass the US to become the world’s leading producers [228]. Figure 22.1 shows the proportion of global soybean production for the top ten producing countries.

Figure 22.1. Soybean production by producer country as a percentage of global production, 1990 to 2005.

Since 1945, soybean has been the world’s most important oil and protein crop, and global output has increased accordingly; in 1949 global production was 12.4 million tonnes in 1949 by 2005 it had increased to 214.8 million tonnes [232, 233]. Although soy oil is expected to lose some market share to palm oil, production is expected to increase by almost 40 percent; from 28 million tonnes in 2003 to 41 million tonnes in 2020. Soymeal production is expected to increase by around 20 percent, from 133 million tonnes to 176 million tonnes [228]. Due to a lack of arable land to expand soybean production in the US and China, most of this expansion will take place in Latin America (ibid).

This increase in global output can be attributed to increased yields, shown in Table 4, and to an increase in the area under soybean cultivation, shown in Table 22.5. Increased yields per hectare may be attributed to breeding and technological changes, such as the application of limestone and fertilisers [231].

Table 22.5. Area harvested for soybean (million hectares) in the top ten producer countries, 1990-2005.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Argentina</td>
<td>4.96</td>
<td>5.93</td>
<td>8.64</td>
<td>14.04</td>
</tr>
<tr>
<td>Bolivia</td>
<td>0.14</td>
<td>0.43</td>
<td>0.58</td>
<td>0.93</td>
</tr>
<tr>
<td>Brazil</td>
<td>11.49</td>
<td>11.68</td>
<td>13.64</td>
<td>22.95</td>
</tr>
<tr>
<td>Canada</td>
<td>0.48</td>
<td>0.82</td>
<td>1.06</td>
<td>1.17</td>
</tr>
<tr>
<td>China</td>
<td>7.56</td>
<td>8.13</td>
<td>9.31</td>
<td>9.59</td>
</tr>
<tr>
<td>India</td>
<td>2.56</td>
<td>5.04</td>
<td>6.42</td>
<td>7.57</td>
</tr>
<tr>
<td>Country</td>
<td>1990</td>
<td>2000</td>
<td>2004</td>
<td>2005</td>
</tr>
<tr>
<td>---------</td>
<td>------</td>
<td>------</td>
<td>------</td>
<td>------</td>
</tr>
<tr>
<td>Indonesia</td>
<td>1.33</td>
<td>1.48</td>
<td>0.83</td>
<td>0.61</td>
</tr>
<tr>
<td>Italy</td>
<td>0.52</td>
<td>0.20</td>
<td>0.25</td>
<td>0.15</td>
</tr>
<tr>
<td>Paraguay</td>
<td>0.90</td>
<td>0.74</td>
<td>1.18</td>
<td>1.97</td>
</tr>
<tr>
<td>US</td>
<td>22.87</td>
<td>24.91</td>
<td>29.30</td>
<td>29.95</td>
</tr>
<tr>
<td><strong>World total</strong></td>
<td>57.1</td>
<td>62.5</td>
<td>74.3</td>
<td>93.4</td>
</tr>
</tbody>
</table>


Between 1990 and 2005, the world total area used for the production of soybean increased by more than 60 percent, from 57 million hectares to 93 million hectares. The increase in area under soybean cultivation has been particularly pronounced in Latin America, where cultivation has increased from 171,000 hectares in 1960 to nearly 40 million hectares by 2005. During the same period the average yield has almost doubled [231].

### 22.3.2. Production practices in Latin America

Within Latin America four main soybean production practices may be discerned, which are outlined below ([228]:9).

- **Smallholder soy farming.** Soy is cultivated in rotation with annual crops such as rice, maize and tobacco. The average farm size is 30 hectares, although those in frontier regions can be up to 200 hectares. Cultivation is either partially or fully mechanised.

- **Traditional soy planting with tillage.** Soy is cultivated in rotation with sorghum, corn, rice or tobacco. In some parts of Argentina, a second crop of soy may be planted. Where irrigation is used, soy or cotton may also be planted in the dry season. Disadvantages of this practice include significant soil erosion, reduction of soil organic matter and a relatively high investment in machinery.

- **No-till planting of conventional (non-GM) soy.** Direct sowing of soy ensures that the soil structure is maintained, reducing soil erosion. In general, a second crop is planted or the crop residues are left as forage for cattle. The costs of (pre-treated) seeds and herbicides are higher. More than seven million hectares in Brazil now use zero-tillage cropping, most of which is cultivated for soybean.

- **No-till planting of GM soy.** Much of the soy cultivated in Argentina and Paraguay uses no-till cultivation of genetically modified, herbicide resistant Roundup Ready (RR) soy. Two soy crops are cultivated annually, and there is no rotation with other crops. Weed control is easy but indiscriminate, and the widespread application of the herbicide glyphosate leads to environmental and health impacts. In Latin American, the dominant production practice in farms ranging from 300 to 10,000 hectares is large scale, fully mechanised production of soy. In Brazil, however, there remains a significant percentage of soy that is produced by smallholders. This share has declined in recent years, although in 2003 still accounted for between 15 and 20 percent of soybean production [228].

### 22.4 Economics

Soy is produced on a large scale in four Latin American countries: Brazil, Argentina, Paraguay and Bolivia, and in recent years has become the single most important agricultural export for all four countries [228]. Thus a key risk for these economies and soy producers is dependence on an unstable international market, which is subject to large fluctuations [229]. These oscillations, the high mechanical investment required in many production systems and significant economies of scale favour large producers. Indeed, since the 1980s large scale soy farming has been the dominant
production practice in Latin America. This trend is particularly harmful to small-scale producers who do not own their own land, instead relying on alternative land tenure arrangements [228-230]. Large-scale, mechanised soy production also results in fewer jobs; while smallholder agriculture in Brazil creates one job per 8 hectares, mechanised plantations may employ as few as 1 person per 200 hectares [228, 229].

In addition, the current structure of agricultural markets in Latin America means that the majority of the profits go to only a small percentage of the population. Currently, two companies, Cargill and Archer Daniels Midland, control more than half of the global trade in grain [230].

22.4.1. Global trade in soy

Ultimately it is the global demand for soybean that will determine the rate and extent of expansion of soy cultivation in Latin America. The EU is the main global importer of soy, in 2003 importing almost 40 million tonnes of soy products. China, which is undergoing strong import growth, imported around 20 million tons of soybean and oil [228]. Other main importers of soy products are Japan, Mexico, Taiwan, Thailand, Indonesia, South Korea, Iran, Bangladesh, Russia, Morocco and Egypt.

By 2020, global demand for soy is expected to rise by 60 percent to 300 million tonnes, largely driven by population growth and increasing per capita income (ibid). While the United States is currently the leading supplier of soy, exports have remained stable due to increasing domestic demand for soy. Because more than 80 percent of the US crop is from genetically modified (GM) soy, US imports to the EU have declined. Brazil, where the cultivation of GMOs is restricted, now supplies more than 60 percent of EU soybean imports [228].

22.4.2. The economics of soybean as a biodiesel feedstock

A number of economic and environmental advantages of biodiesel have been cited, including reduced reliance on imports of crude oil, agricultural support through the provision of new labour and market opportunities, and wide acceptance by the automotive industry [234]. However, the major economic factor to consider for input costs of the production of biodiesel is the feedstock, which accounts for between and 80 and 85 percent of the input costs, followed by energy and water [235]. Other input costs include labour, methanol and catalyst.

Most of the biodiesel that is currently produced uses soy oil, methanol and an alkaline catalyst. However, the high value of soybean oil as a food product makes production of a cost-effective fuel challenging [194]. In 2005, the estimated production cost of soybean biodiesel in the US was $0.55 per diesel energy equivalent litre (EEL), whereas diesel wholesale prices averaged $0.46 per litre [236]. There are also limits to the amount of biodiesel that can be produced from soy; a recent study by Hill et al. [236] concluded that even if the entire US soybean crop was dedicated to the production of biodiesel, it would meet only 6 percent of US demand for diesel.

Biofuel is increasingly being cited as a substitute for oil-based fuels, and increased production has led to raised expectations about their potential. However, there is growing concern about the impact of rising commodity prices on the global food system. In 2006, world food prices increased by 10 percent caused by increases in the price of corn, wheat, and soybean; this was primarily due to demand-side factors, including the rising demand for biofuels [237]. Rapid growth in the demand for
biofuels will therefore raise the prices of agricultural commodities, including soy. This increase may have negative economic and social effects, particularly on the poor who spend a larger share of their income on food [230].

22.5 Environmental and ecological impacts of soybean

This section discusses the key environmental impacts of the cultivation of soy, deforestation, biodiversity loss and the use of GMOs; all of which relate to wider concerns about unsustainable land use and agricultural production methods. Increased soy production is also likely to lead to other environmental impacts, such as water scarcity and soil erosion, and there are also concerns about leakage effects (transfer of unwanted activities). To date there have been no peer reviewed life-cycle greenhouse gas studies for biodiesel from palm oil, jatropha or soybean [238].

A recent study by Zah et al ([33], reviewed in Scharlemann and Laurance, [239]) provided an assessment of the environmental costs and benefits of different transport biofuels. The authors compared gasoline, diesel, and natural gas with 26 different biofuels produced from a range of crops. The total environmental impact of each fuel was calculated by aggregating natural resource depletion and damage to human health and ecosystems into a single indicator; the other indicator assessed the greenhouse gas emissions relative to gasoline. While most of the biofuels (21 out of 26) reduced GHG emissions by more than 30 percent relative to gasoline, just under half (12 out of 26)- including US corn ethanol, Brazilian sugarcane and soy diesel, and Malaysian palm oil diesel- had greater aggregate environmental costs than fossil fuels. Although there are some limitations to the methodology, such as the use of a single number to evaluate all of the environmental costs, and no assessment of the social impacts associated with the use of biofuels, the study is an important step in assessing the full environmental costs of biofuels. This study demonstrates that not all biofuels are beneficial when their full environmental costs are considered, particularly biofuels produced from corn, sugarcane and soy [239].

22.5.1 Expansion of soy production

The global demand for soy products is increasing, yet despite yield increases the area currently under soy cultivation will soon be insufficient to meet demand, particularly as demand for biofuels grows. It is expected that the majority of future soy expansion will occur in Latin America, particularly Brazil and Argentina. In Brazil alone, Casson [207] estimated that soybean could increase three-fold by 2050, from 23 million hectares in 2005 to 54 million hectares. Dros [228] highlights several factors that have lead to expansion of soybean cultivation in Latin America:

- Poor law enforcement which facilitates illegal acquisition of land, deforestation, payment of below minimum wages and failure to meet environmental regulations
- ‘Perverse incentives’ which favour the production of raw materials over value added, processed products. One example is the Brazilian Kandir Law, which promotes the export of soybeans but taxes exports of processed soy products
- Favourable market conditions for agricultural exports. For example, ‘technology packages’ provided by soy traders ensure that soy production is economically attractive although it may not be the most suitable crop either ecologically or socially.

Other factors include the availability of cheap land, a suitable climate and a supportive transport and financial infrastructure [228].
22.5.2 Deforestation and biodiversity loss

The expansion of soy is a major driver of deforestation and habitat loss in the South American producer countries. Many of the habitats threatened by soy expansion biologically diverse, many with high levels of endemism, and are globally unique. These ecosystems include the Chaco bush savannah of Argentina, Bolivia and Paraguay, the Yungas subtropical forest of Argentina, and the Cerrado savannah and Amazon rainforest of Brazil. Agricultural expansion, dominated by soy, has already led to the virtual disappearance of the Brazilian Atlantic forest in the 1970s and 80s, and now threatens the Bolivian Atlantic forest [228]. Many of the environmental impacts caused by soybean are thus brought about by expansion into natural, largely undisturbed, habitats. Governments must therefore provide incentives for expansion into areas that are already altered or disturbed, rather than these important ecosystems [238]. The expansion of soy into these habitats will lead to further threats because expansion is associated with other activities that result in habitat loss, such as pasture development, logging, development of transport infrastructure and charcoal production [207, 240].

The drivers of deforestation have changed over time, forestry (1930 - 1960) and cattle ranching (1960 -1980) have traditionally been the most important. However, more recently the expansion of mechanised soy farming has been the major cause of deforestation [228]. In addition to changing drivers of deforestation, the use of deforested areas is also changing. A study by Morton et al. [241] showed a shift between 2001 and 2004 from the use of deforested areas for pasture to their use for cropland; this shift was related to mean annual soybean price and favourable market conditions for soybean. It is argued that this rise in the importance of deforestation for cropland represents a new paradigm, defined by larger clearing sizes and faster rates of forest conversion than previous pathways [241].

In addition, as an annual crop the environmental impacts of soybean plantations are greater than many other crops or cattle ranching; soy is less efficient at using water and nutrients, which may lead to a decline in water quality and soil degradation. The biodiversity loss associated with large scale, mechanised plantations is also greater as native vegetation is cleared using machinery and agrochemicals. Clearance in this way also reduces the opportunities for habitat restoration [240].

22.5.3 Genetically modified soy

The use of genetically modified (GM) soybean has lead to negative environmental and social impacts, leading to protests from NGOs and individuals and communities affected by its use. The debate about genetically modified organisms (GMOs) is well documented (see, for example, Nuffield Council on Bioethics, 1999; 2003) and will not be discussed here. However, with regards to the use of GM soy, there is concern about the impact on biodiversity, through the transfer of genetic material to wild species. This is of particular concern to the biodiverse Latin American countries [240].

GM soybean is the most widely cultivated GM crop in the world, occupying around half of the total area of GM crops ([231]; 80 percent of US soybean is from GM seed, while nearly 100 percent of Argentinean soy is GM [228]. In Brazil, despite a ban on GM soy in 1999, it is estimated that as much as 10 percent of Brazilian soybean is genetically modified through illegal imports from Argentina [240]. In 2003 in
Paraguay, the cultivation of GM soy was legalised after a study demonstrated that as much as 80 percent of soy was genetically modified [228].

Roundup Ready (RR) soy has been genetically engineered to contain gene sequences that are resistant to glyphosate, the active ingredient in the herbicide, Roundup. In Argentina, the use of RR soy has promoted the development of large scale, mechanised farming of soy, with ensuing expulsion of small farmers and rural workers [242]. The use of GM soy is also associated with the intensive use of agrochemicals, despite the premise that a single herbicide would be able to control all weeds. In Argentina, the use of glyphosate increased from 1 million to 150 million litres between 1994 and 2003 [228]. Resistance to glyphosate has emerged in some weeds, requiring a ‘cocktail of highly toxic herbicides’ (ibid: 23). Widespread and indiscriminate use of glyphosate has had negative impacts on both human and animal health, and there have been reports of intoxication amongst workers and neighbouring communities. Many communities lack the capacity to recognise and treat the symptoms of exposure to agrochemicals [242]. Indiscriminate use of glyphosate has also been blamed for the destruction of soil microbial life, which has led to sterile soils [228].

**22.6 Social context**

Biofuels have the potential to provide a great many opportunities including assisting rural development and reducing poverty. However, whether these opportunities are realised depends on how and at what scale biofuels are developed, and under what conditions this development takes place [230, 238]. In South America these potential socio-economic benefits are not being delivered, in large part due to the large scale, mechanised agricultural systems typically used for soy cultivation.

There are numerous health problems associated with the intensive and indiscriminate application of agrochemicals used in many such production systems; the use of agrochemicals affects the health of both humans and ecosystems. In Paraguay the expansion of soy plantations has led to a threefold increase in the import of agrochemicals [243]. The presence of silos and agrochemical stores also carry health risks, particularly because security and environmental laws determining the storage of agrochemicals are rarely enforced (ibid). In addition to the negative health impacts, indiscriminate spraying also affects surrounding smallholdings and homes, damaging cash crops and reducing food security [243]. In Argentina, the shift from traditional cattle ranching to the production of soy has caused a drop in food and dairy production for domestic markets [228].

There are relatively few rural employment opportunities in soy production. While smallholder agriculture in Brazil may create as many as one job per 8 hectares; mechanised plantations may employ as few as 1 person per 200 hectares [228, 229]. Labour conditions of many soy plantations are generally poor, and in 2003, 120 people were found to be working under slave-like conditions in a ‘state of the art’ soy plantation [228].

Many rural and indigenous people rely on alternative land tenure arrangements and large soy farms lead to a concentration of land ownership and income. This process results in driving farmers without clear titles off their lands, destroying livelihoods and traditional agricultural systems in the process [230]. This displacement may result in migration to the peripheries of urban areas, or the establishment of new local frontiers, increasing pressure on natural habitats [240]. In Paraguay, the expansion of
soy monoculture has led to violent clashes between unarmed local communities and the police, repression and forced evictions. In 2005, two peasants were killed by armed militia during protests against soy producers attempting to buy their land for the production of GM soy [243].

22.7 Planned soy expansion in South America

Despite the numerous environmental and socio-economic impacts that arise from the production and expansion of soy, there are plans for expansion in all four of the major Latin American soy producers. The following draws largely from Dros [228].

- Over the next decade, Argentina plans to double the production of grain and oilseed to reach 100 million tonnes. Since 1997 the proportion of total area of arable crops planted with soy has doubled, increasing from 24 percent to 50 percent in 2004.
- Under the Bolivia Competitiva plan, the Bolivian government aims to double its soy exports within 10 years. The plan also intends to increase productivity by 60 percent, which would reduce the amount of additional land required. However, over the past decade the productivity of soy in Bolivia has been declining. Dros comments ‘at current productivity, the area planted with soy would have to increase by 1.2 million hectares’.
- As the main agricultural export in Brazil, there are numerous government programmes to support the expansion of soy. Despite much evidence to the contrary (see above) the potential impact of soy on local economic development is also increasing interest in the growth of soy. Of the 70-100 million hectares that have been deemed suitable for soy cultivation, only 21 million hectares are currently used for soy. Of the rest, 30 to 40 million are under natural Cerrado vegetation, 7 million are forested, while between 12 and 32 million are planted pastures.
- By 2008, the Paraguayan producers’ association, CAPECO, had planned to increase the area cultivated for soy from 1.7 million hectares in 2004 to 3.5 million hectares. Although this expansion was to take place within existing cattle raising areas, legal and illegal deforestation for soy is common practice.

22.8 Constraints

Competition with other uses of soy products, particularly with food markets, and rising concern about food prices make it seem likely that this will remain a constraint on the use of soy as a major biodiesel feedstock for the foreseeable. Compounding this, the high value of soy for food products makes the production of soy biodiesel economically challenging. Growing concerns about the negative environmental and social impacts of soy production, particularly as a major driver of deforestation and habitat loss, may also constraint the social acceptability of this feedstock. In terms of technical constraints, while it seems likely that yields will continue to increase due to advances in plant breeding and technology, increasing resistance of GM crops to agrochemicals may lead to stagnating yields.

22.9. Conclusion

The main driver of soybean expansion is the increasing demand for soy products. Yet, despite yield increases over the past decade the area currently under soy cultivation
will soon be insufficient to meet demand, particularly as demand for biofuels grows. The majority of future soy expansion is expected to occur in Latin America, particularly Argentina, Bolivia, Brazil and Paraguay. Many of the areas that are deemed suitable for the expansion of soy production are in globally unique, biodiverse ecosystems, such as the Amazon and Yungas cloudforest. Expansion of soy in these habitats will only exacerbate environmental impacts including deforestation, biodiversity loss, and unsustainable land use practices.

Although biofuels have potential opportunities for rural development, few of these benefits have been realised in South America. Indeed, soy production has led to many negative social impacts such as health impacts from exposure to agrochemicals, and the concentration of land ownership and income, which outweigh any positive impacts.

Although there is little available literature on the sustainability of soy as a feedstock for biofuel, it is used in biodiesel in both the EU and the US. While the US is the largest producer of soybean, and potentially able to meet increased demand, the EU is the main global importer of soy and will have to meet increasing demand through imports. With little literature on the demand for soybean as a biodiesel feedstock it is difficult to predict how this demand will affect the expansion of soy. However, it is certain that the use of soy as a feedstock will drive demand and thus soy expansion, with all the environmental and socio-economic impacts it inevitably brings. Governments need to be more selective about the biofuel feedstocks they support. In addition, social and environmental standards for more sustainable soy production are urgently needed.
23. Sugar Cane (Saccharum officinarum L.)

23.1 Feedstock description
Sugarcane and sugar are of global economic significance. Sugarcane is produced in 103 countries; 15 countries devote 25% or more of their land to sugar and sugar is the first or second most valuable export for 13 countries [244]. Sugar cane is a perennial C₄ plant with a high sugar content, low fibre content, relatively pure juice, is ecologically relatively adaptable and relatively resistant to pests [245]. Due to its high capacity to fix energy in limited time and space, sugarcane is widely considered to be one of the world’s most important economic plants (Hus, 1989, in [245]).

23.2 Feedstock origin
Sugar cane grows best in the tropics and sub-tropics, roughly between 37°N and 31°S, and within this region specific cultivars are bred to suit climatic variations [245]. Sugar cane generally prefers a heavy soil with high nutrient content and a high water retention capacity; its most favourable tropical and subtropical temperature is 25-26°C, though some cultivars can tolerate colder climates (ibid). A high level of rainfall is required: usually 1500-1800mm p.a.; in hot and dry conditions 2500mm or more p.a. may be needed ([246] in [245]).

23.3 Production
Sugarcane is usually propagated via stem cuttings, which are best taken from unripened canes that are 8-9 months’ old and which are from the locality in which they are to be planted. 1ha of sugarcane can provide enough stems to plant 5-6ha. A pre-planting fungicide and insecticide are recommended ([246] in [245]). Recommended planting for the cuttings is by laying them end to end in furrows that are 1.2-1.5m apart and 30-40cm deep, and then shallow-covered. 15,000-20,000 cuttings are required per ha (ibid). Herbicide is recommended for use before the leaf canopy can close, though the inter-row soil should be mechanically weeded (ibid). Fertiliser should be applied with the initial watering after planting, and then again three months later ([247] in [245]). Herbicides are also used subsequently to control a variety of insect pests.

Table 23.1 below shows how Sugarcane yield is strongly affected by the planting date and hence the climate experienced over the 12 month growing cycle ([247] in [245]).

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Month of Planting</th>
<th>Theoretical maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>January</td>
<td>May</td>
</tr>
<tr>
<td>Dry matter (t/ha)</td>
<td>34</td>
<td>27.5</td>
</tr>
<tr>
<td>Fresh matter (t/ha)</td>
<td>136</td>
<td>110</td>
</tr>
<tr>
<td>Fresh leaves (t/ha)</td>
<td>46</td>
<td>49.5</td>
</tr>
<tr>
<td>Cane stalk (t/ha)</td>
<td>90</td>
<td>60.5</td>
</tr>
<tr>
<td>Saccharose (%)</td>
<td>14</td>
<td>8.5</td>
</tr>
<tr>
<td>Saccharose (t/ha)</td>
<td>12.6</td>
<td>5.14</td>
</tr>
<tr>
<td>White sugar (t/ha)</td>
<td>10</td>
<td>3.45</td>
</tr>
</tbody>
</table>
Harvesting with sugarcane harvesters is best done after a dry period of two months, as this stops plant growth and raises sugar content ([246] in [245]). The sugarcane is processed by diffusion or pressing to remove the saccharose-containing juice from the stalk, while the remaining ‘bagasse’ can be burned for heat or electricity or further processed for building materials and other purposes [245].

Husz ([247] in [245]) describes the sugar refining process further: crystallization and centrifuging provides a 96% pure product described as raw sugar. Further washing and centrifuging gives a 99.8% pure product, white sugar. The molasses removed during these steps can be removed to produce alcohol. One tonne of sugarcane can produce approx 100kg of sugar, 30kg of bagasse and 40kg of molasses, the latter of which can produce 10 litres of alcohol. If processed for alcohol alone, 1t of sugarcane can produce approx 70 litres of alcohol ([247] in [245]).

23.4 Economics

This section particularly considers the wider and longer term context in addition to contemporary sugar cane economics. Ethanol from sugarcane grown in Brazil is by far the cheapest biofuel today. South America and Africa have a large potential to increase biofuel production. Ethanol may also be efficiently produced in South-East Asia and Australia, though the availability of suitable land will place tighter constraints on production there [248].

In general, more than half of the production cost of biofuels is determined by the price of the feedstock [248]. Given the enormous requirements for land and the competition with food and fibre, biomass feedstock prices may not decline as much as is often assumed (ibid). Indeed, in Brazil, a country with relatively ample space for agricultural production, prices for land and feedstocks have gone up in response to the increased demand for biofuels (ibid).

Doornbosch and Steenblik [248] cite work on 2005 and projected 2030 future costs of producing ethanol from different feedstocks as estimated by the IEA [249]. Brazil’s costs, at $0.20 per litre ($0.30 per litre of gasoline equivalent) for ethanol produced in new plants, are the lowest in the world. Even before the recent rise in maize prices in the United States, grain-based ethanol cost some 50% more to produce than cane-based ethanol in Brazil, and 100% more than in the EU. These costs do not include the costs of transporting, splash blending and distributing ethanol, however, which can easily add another $0.20 per litre at the pump (ibid). The cost estimates also exclude subsidies to the crop or to the biofuel. By 2030, ligno-cellulosic ethanol is projected to fall to a price similar to that of 2030 sugarcane ethanol, i.e. circa 20-25 US cents/litre (ibid).

As agricultural feedstock dominates the production costs of liquid biofuels, the markets for biofuels and agricultural products interact [248]. Due to crop substitutability, world biofuels markets will also be related to crop markets that are not used as an input for biofuel production per se ([250] in [248]). Moreover, crops tend to compete for the same inputs, land, fertilizers and water (where irrigation is necessary. This makes it particularly difficult to project the future costs of ethanol, its likely production method and the role of mineral oil prices. The role of policy intervention can be critical. For example, The World Bank [250] compares ethanol prices with world gasoline prices and sugar prices from January 1990 to April 2007. The results show that even in Brazil — the most cost-effective ethanol producer in the world — for most of this period turning sugar into ethanol was a lower-value use of
the sugar than selling it on the world market would have been. Despite very high world petroleum prices, soaring world sugar prices made it difficult for ethanol to be more profitable than sugar during 2006 [248]:33.

Doornbosch and Steenblik [248] note that the OECD considers the bioenergy industry to become a key factor in the functioning of agricultural markets, with food prices expected to rise between 20% and 50% over the next decade. They note that it is opposite to the price developments projected in the models of the IEA’s World Energy Outlook 2006 [249], which assumed a further declining price of agricultural feedstocks because of increased productivity. Doornbosch and Steenblik [248] observe that the reason for this discrepancy may be that the feedback effects between the agricultural and biofuels market are not modelled in the IEA’s models but agricultural prices are taken exogenously.

Moreover, Doornbosch and Steenblik [248] note that as higher oil prices increase biofuel production costs as well as the demand for biofuels, this pushes feedstock prices up. They note that Kojima et al. [250] thus suggest a threshold level of diversion of a given crop to the biofuels market of about 10%. A higher share of biofuels will link the price movement of that crop to the world petroleum market. This is also the reason that Kojima et al. ([250] in [248], ibid) conclude that biofuels are unlikely to become the solution to rising crude-oil prices.

23.5 Environmental and ecological impacts

23.5.1 Site impacts

This section draws heavily on WWF [251]. In general, the cultivation and processing of sugar lead to environmental impacts through the loss of natural habitats, intensive use of water, heavy use of agro-chemicals, discharge and runoff of polluted effluent and air pollution. This leads to the degradation of wildlife, soil, air and water where sugar is produced and in downstream ecosystems. Impacts relating to irrigation of sugar cane and pollution runoff are of particular concern [251].

Erosion is a significant issue in areas under sugar cane or beet cultivation, particularly in tropical areas (where most cane is grown), since erosion rates in tropical agroecosystems are usually greater than the rate of soil formation. Sugarcane is currently grown on many steep slopes and hillsides, leading to high rates of soil erosion resulting from the increased rates of water runoff on sloping land. It is recommended that cane should not be grown on slopes greater than eight percent, although slopes of 20-30 percent are planted, for example, in parts of the Caribbean and South Africa [251].

Although zero tillage farming can promote compaction in heavy soils, since the soil is not regularly loosened, conventional tillage commonly promotes erosion by exposing soil aggregates to rainfall. Conventional tillage i.e. deep ploughing, also drastically changes soil structure and is probably one of the most disturbing agricultural practices for soil fauna. In addition, tillage in both cane and beet cultivation systems has been found to promote organic matter breakdown leading to declines in soil structure and health (ibid).

Surface sealing and crust formation can occur on heavily compacted cane growing soils, resulting in a relatively impermeable layer at the soil surface. Sodic soils are particularly vulnerable to sealing, and the loss of organic matter, often associated with cultivation, can also render soils more susceptible to sealing. Sealing reduces water
infiltration and increases runoff, enhancing the risk of erosion and pollution of waterways, as well as reducing the water available to the crop and inhibiting seedling emergence (ibid).

Salinisation of soils is a problem that principally affects cane growers rather than beet growers and typically results from over-irrigation, inadequate drainage and cultivation in a flood plain or where sea water intrusion occurs. Salinity of soils has been linked to serious cane yield declines. For example, sugar cane yields in Pakistan on soils affected by water logging and salinity are up to 50% lower than on unaffected land. An estimated 40% of the cane growing areas of Pakistan have salinity problems (ibid).

Increased soil acidity affects plant health and crop yield in some parts of the world. Acidification is also more prevalent in cane than beet growing areas, largely due to the use of inorganic nitrogenous fertilisers such as urea and ammonium sulphate. Under high rainfall conditions nitrate leaching occurs, which also promotes acidification. For example, soil organic carbon declined by about 40% between 1979 and 1996 in cane cultivation areas in Papua New Guinea (ibid).

The sugar industry is also associated with major new infrastructure in rural areas, which has its own impacts. For example, in Australia this has included damming of the Burdekin, Tully and Barron Rivers, which has altered the pattern of freshwater flow into the Great Barrier Reef lagoon. Cane growing has shown to increase sediment and nutrient loads, particularly following heavy rainfall, which can carry these materials into the sea, reducing water quality and impacting on inshore reefs (ibid: 8). Over the last 60 years the construction of dams, barrages and irrigation systems in Pakistan have lead to a 90 percent reduction in the amount of freshwater reaching the Indus Delta. Sugarcane cultivation is consuming significantly more water per unit area than any other crop grown in the Indus Basin. The Delta supports the world’s largest expanse of arid land mangroves, which rely on an inflow of freshwater (ibid: 9).

Phosphorus-rich runoff from sugar cane fields in Florida is held largely responsible for the decline of the Everglades (ibid: 9). Discharge of effluents from sugar mills and from processing by-products (e.g. molasses) has also been shown to result in the suffocation of freshwater biodiversity, particularly in tropical rivers that are already naturally low in oxygen (ibid: 10).

Although the greatest land clearance for sugar cane cultivation is historic, the area under cultivation in some areas has continued to expand in recent years. For example, a programme to use sugarcane as the raw material for fuel alcohol production led to the deforestation of new areas in the State of Alagoas, Brazil, such that only three percent of the original rain forest cover remains. Recent studies have also shown an 85 percent reduction in Brazilian Cerrado vegetation in the regions of Franca, Araraquara, Ribeirao Preto and Sao Carlos due in part to clearance for sugar cane cultivation (ibid: 11). In the Indian state of Maharashtra, sugar cane covers just three percent of the land yet uses around 60 percent of the state irrigation supply and is a cause of substantial groundwater withdrawals; the water table in places has dropped from 15 metres to around 65 metres in the past 20 years (ibid: 12).

In many sugar producing countries, the cane fields are burnt immediately before harvesting for easier cutting, post harvest cultivation and pest control. ‘Green cane’
harvesting (without burning) is also practiced (see below). Pre-harvest burning leads to:

- **Air pollution:** substantially elevated levels of carbon monoxide and ozone in the atmosphere have been found around sugarcane fields in the state of Sao Paulo, Brazil, at the time of pre-harvest burning.
- **Soil degradation:** there is evidence that sustained pre-harvest burning of sugar cane can contribute to a decrease in soil quality, by causing a decline in soil microbial activity and the physical and chemical properties of the soil; pre-harvest burning may be responsible for as much as 30 percent of the annual nitrogen removal in a cane crop (ibid: 17).

### 23.5.2 Mitigations

WWF (ibid:18) summarise the range of Better Management Practices in use or under development that are intended to mitigate the main environmental and social impacts of sugar growing and processing.

In relation to water use, larger-scale farmers are able to implement advanced commercial drip, sprinkler, or centre-pivot systems while small-scale farms, and even some large estates, mainly use inefficient flood irrigation. Low-cost drip systems are available for small-holders, provided that micro-credit is available for purchase of the equipment and sufficient ongoing technical support is provided. Furrow irrigation only requires a ridger to cut the furrows and with alternate furrow irrigation substantial water savings can be made. Improved irrigation techniques can also be combined with trash mulching for further water savings (ibid: 19). Irrigation scheduling, including the use of tensiometers to monitor soil moisture, and tail-water recycling (where water-runoff from field is collected and reused for irrigation) are also ways of improving irrigation management (ibid: 20).

Drip irrigation can decrease fertiliser and pesticide requirements (ibid: 22). Fertiliser is applied through a drip system, delivering nutrients only to the plant base (surface drip) or root zone (sub-surface drip). The method combines the increased water use efficiency of a drip irrigation system with the potential to manage fertiliser applications more effectively. In addition, the application of soil pesticides can be reduced by 30 percent when applied directly to the root zone. Additional methods for reducing fertiliser use in cane cultivation systems include a more site specific assessment of fertiliser requirements, cultivation of leguminous green manure crops during fallow periods or in rotation, the use of biofertilisers (combinations of nitrogen-fixing micro-organisms and organic amendments), green cane harvesting and press mud, a sugar cane mill by-product which is particularly effective for reducing phosphorus deficiency in cane (ibid: 23).

Re pest management: there are numerous examples of successful Integrated Pest Management (IPM) programmes in sugarcane. IPM combines biological control with a variety of other appropriate physical, chemical and mechanical control methods to achieve a more sustainable approach to pest control. For example, Papua New Guinea, considered to be the centre of origin of sugarcane, controls the stem boring larvae of the of the noctuid moth (*Sesamia grisescens*) via resistant cultivars and optimum planting times, rational pesticide use, biological control, close monitoring of the situation in the crop and the use of pheromones for trapping or mating disruption (ibid: 25).
Another example: the white grub (Phylophaga sp.) pest which feeds on the roots and causes severe losses in cane production is typically controlled using high quantities of the chemical Ethroprop. However, a fungus (Beauveria bassiana) which feeds on grub’s larvae, can be used efficiently to control the pest. In addition, white grub adults can be caught by the use of night-illuminated traps during larval production.

Valuable lessons can be learned about the impact of pesticides on non-target species: for example, populations of the froghopper pest in cane cultivation in Guyana declined to low levels after attempts at chemical control were discontinued, even without the release of specific biological control agents. This reduction in pest numbers was due to the recovery of existing natural enemy populations following the withdrawal of insecticide treatment (ibid).

A wide range of measures have been proposed and investigated for the reduction of soil erosion and improvement in soil quality in sugar cane and beet cultivation systems. These measures include trash mulching in cane cultivation, maintenance of beet as part of a crop rotation, terracing, contour and strip planting of cane on slopes, maintenance of ‘live barriers’ (hedgerows, riparian zones), and modified (reduced or minimum) tillage. The shift from pre-harvest cane burning to ‘green cane harvesting’ (where the cane is harvested without being burned first) and ‘trash-blanketing’ (where the cane leaves are cut from the plant and left on the soil as a mulch while the stalks are taken away for processing) (ibid: 26).

A wide range of measures has been proposed and investigated for the reduction of soil erosion and improvement in soil quality in sugar cane and beet cultivation systems. These measures include trash mulching in cane cultivation, maintenance of beet as part of a crop rotation, terracing, contour and strip planting of cane on slopes, maintenance of ‘live barriers’ (hedgerows, riparian zones), and modified (reduced or minimum) tillage. Retention of a cane trash blanket can provide up to 10-20 t/ha of organic matter from the cane, left on the soil surface after harvest. This increases microbial biomass, carbon and basal respiration in the surface soil, as well as earthworm numbers. In the long term, trash blanketing can be expected to raise soil organic matter content by around 40 percent after 60-70 years (ibid: 27). Modified tillage can also help to prevent soil erosion, while zero tillage has reduced soil loss rates on slopes of 5-18 percent in Australia, from 148 t/ha/year (conventionally cultivated) to <15 t/ha/year (ibid: 28).

There are also processing-related impacts that can be mitigated. Reducing the impact of pollution from sugar mills, if not the level of pollution itself, can be achieved by siting sugar mills downwind of populated centres, to minimise nuisance from gaseous emissions. Isolation from natural ecosystems can help to minimise the impacts of effluent discharge on rivers and coastal areas. The volume of fly ash can be reduced by drying bagasse prior to its use as a boiler fuel, which increases the efficiency of burning and reduces emissions. Fly ash extracted from boiler chimney gas can be used as a filtration aid in the sugar mill and can also be used for the removal of pesticides from wastewater. Up to 98 percent removal of lindane and malathion pesticides was obtained using fly ash under optimum conditions in India, providing an inexpensive and effective option for filtering waste water (ibid: 32-33). Basic dust control measures are also generally cheap and simple to install. Reduced gaseous emissions and odour can be achieved by using hydrogen peroxide in place of sulphur dioxide in sugar mills, also resulting in a higher quality white sugar product while requiring no new equipment. A range of techniques is available for treating liquid sugar mill effluents, including the treatment of mill sludge with micro-organisms that accelerate
the rate of decomposition. Some Indian sugar mills recycle treated effluents as make-
up water for cooling towers and spray ponds (ibid: 29).

Natural habitats within the farm landscape can benefit from appropriate planning and
management, including the restoration of degraded land to provide wildlife corridors
and maintenance of watercourses. Farm and landscape plans, of all sorts from
informal agreements to highly technical documents, provide a mechanism to gain
productivity and to reduce impacts (ibid: 30).

Re soil conditioners and fertilisers, filter press mud from cane mills is often
incorporated into soils as a conditioner and fertiliser. A number of studies suggest that
vinasse and treated waste water from sugar cane mills is suitable for irrigation,
although there is concern that these products have the potential to pollute soils and
groundwater and cause salinisation, especially if used in large amounts; irrigation
with cane effluent was found to suppress germination of peas in Balrampur, India.
Bagasse has been used as a mulch to aid re-vegetation and stabilisation of denuded
land on road verges and can also be used as a substrate for mushroom cultivation,
with the cultivation residue potentially used in animal feed. Bagasse is also used in a
number of countries in production of paper and particle board. In combination with
micro-organisms, sugar cane filter cake was superior to farmyard manure and poultry
manure in sustaining crop yield and soil properties in irrigated wheat fields in
Faisalabad, Pakistan (ibid: 31). Bagasse is a potentially valuable cellulose source for
the production of chemicals, such as pentosans (including furfural) and allied
substances.

23.5.3 GHG displacement

Doornbosch and Steenblik [248] refer to IEA [249, 252] and Farrell et al [253] in
estimating the GHG benefits of sugarcane and other current ethanol sources. The best
performance of the current ethanol options is achieved by ethanol from sugarcane in
Brazil, with the potential to reduce total life-cycle GHG emissions by up to
90%relative to gasoline. Ethanol from cellulosic feedstocks is next best, with typical
estimates placing their reduction in the range of 70 to 90% [252]. In some cases, the
savings could approach and even exceed 100% with, for example, the cogeneration of
electricity that displaces coal-fired electricity from the grid (though so far these
estimates mainly come from engineering studies and only a few large scale production
facilities). Next in terms of GHG efficiency are ethanol from sugar beet and biodiesel
from Malaysian palm oil and EU rapeseed respectively, with GHG reductions of
roughly 40% to 50%. Finally, ethanol from starchy grains yields the smallest GHG
reduction. Re the latter, Farrell et al. [253] compare several reports published on
maize (corn) ethanol production in the US and conclude that the “best point estimate”
would be a reduction of GHG emissions of only 13% because fossil fuels are used as
a fuel in the production process and the energy inputs are almost 80% of the energy
output. Even then, one has to assign a “credit” to the major co-product of grain-based
ethanol: dried distillers grains with solubles (DDGS) [248].

23.5.4 LCA performance

The Swiss Institute, EMPA ([33] in[248]) performed a full life cycle assessment of
some 26 biofuel types, though some were identical but of different nationality,
comparing these to LCA of transport fuels derived from petroleum and natural gas.
Indicators included damage to human health, ecosystems and the depletion of natural
resources, all aggregated in a single indictor (UBP). Most biofuels were found to have
an overall environmental performance worse than gasoline, though with a widely differing relative performance. Maize-based ethanol in the USA earned a particularly poor environmental score, and ethanol from sugar beets and sugarcane scored only moderately better than gasoline in terms of their overall environmental impacts. Biodiesel scores were also generally negative. Only when waste products such as recycled cooking oils are used do their overall environmental performances fare better than that of gasoline. Biofuels made from woody biomass were rated better than gasoline in all cases.

### 23.6 Social context

There are significant social impacts of pesticide use when these are not properly regulated. Many large-scale pesticide applications, including rodenticides, are carried out using aircraft. The negative impacts of pesticide use on human health are considerable; the WHO estimates that there are 25 million cases of acute chemical poisoning in developing countries each year related to pesticide use in agriculture [251].

The following overview of social and community impacts of sugar production is from a presentation by the International Labor Rights Fund to the Better Sugarcane Initiative [254]. Mechanization is in general replacing human labourers. In Brazil, a machine can cut the same amount of cane per day as 80 workers, and can operate 24 hours per day. Nevertheless, sugar cane labourers are often subject to adverse Health and Safety impacts arising from chemical and pesticide use, including aerial spray; a lack of first aid kits in the field; insufficient personal protective equipment; dehydration and the hazards of cane burning. Cane labourers are often migrants and communities are impacted when the local population suddenly expands (e.g. quadruples). Pay discrepancies and exploitation are rife; in Costa Rica: 90% of harvest workers are Nicaraguans and many migrant workers work in exchange for food and housing. In Brazil, half a million people travel 3,000 km to work in sugar. In Nicaragua 83% of cane workers earn less than the minimum wage for agriculture. In Guatemala workers are labouring 12 hours/day, 7 days/week and excessively long workdays lead to accidents. In El Salvador at least 5,000 children work in the sugarcane harvest and child labour is also documented in Brazil and the Philippines (ibid).

There are a variety of contractual and job instability issues in the sugarcane industry. Subcontracted workers generally do not receive the minimum wage, bonuses or social security coverage. These workers cannot organize into unions; 85% of sugar workers in Central America have temporary contracts with no job security. Obstacles to union organization include the temporary nature of their contracts; intimidation by employers; threats of retaliation and blacklisting. In El Salvador, 20% of harvesters and 42% of refinery workers surveyed had been coerced or bribed to prevent them from organizing (ibid).

Housing and hygiene pose further problems. The workers have no toilets and have no potable water in the field. In Guatemala, subcontracted workers camp in the fields and their homes are plastic sheeting strung over poles. Further poverty-related issues include the displacement of rural farmers, concentration of land in a few landowners, and migration to the cities by displaced people.

In response, Ferm (ibid) lists the following strategies and alternatives: awareness raising among workers (to inform them of their rights); encouraging traders to include
international labour standards in contracts with suppliers; the establishment of certification programs such as fair trade; and increasing public awareness via civil society campaigns on child Labour, the plight of subcontractors, the environmental issues and modern slave labour (ibid).

23.7 Applications
In this context, the principal application of sugarcane is as an ethanol feedstock, for vehicle transport fuel (in internal combustion engines). Uptake has been facilitated by the development of flex-fuel vehicles that can run on any ratio of gasoline (petrol) / ethanol blend, up to 85% ethanol. In 2005, Brazil’s carmakers sold more vehicles adapted to run on alcohol than conventional petrol-driven models, with flex-fuel cars taking 53.6% of the Brazilian market [255].

23.8 Constraints
In general the distribution of future biomass production for bioenergy is likely to reflect the distribution of natural forest and pasture in both countries and regions, plus the fact that biomass is more productive in tropical areas [256]. At issue is the extent to which these will be used, given the adverse GHG consequences of their conversion and growing public awareness of this. Often the arguments turn on the claimed and actual availability of so-called degraded land. Thus, re Brazilian sugar cane, Hirsch [257] cites Maurício Tolmasquim from the Brazilian government-run Energy Research Corporation (Empresa de Pesquisa Energética), as stating that the geographical distribution of existing and new ethanol distilleries (always close to plantations) shows (a) that the Amazon would not be threatened by an expansion of sugar cane and (b) that a doubling of the current area in Brazil planted with sugarcane (about 7m ha) can be accommodated easily without threatening either food production or unconverted ecosystems, as there are vast tracts of degraded pasture land available for cultivation with just a slight increase in cattle productivity per hectare. In contrast, Hirsch (ibid) notes that Prof Ricardo Abramovay of the University of Sao Paulo (and others) query the lack of monitoring and control of expansion of sugarcane into the Cerrado, a huge and biodiverse savannah in NE Brazil. Hirsch says that there is still a widespread attitude that savannah is “un-used” land ripe for development, even though it is an ecosystem with some of the highest levels of plant and bird endemics in the world. And it is precisely where the sugarcane frontier is concentrated. In summary, the constraints to sugarcane expansion will be defined by the interplay of far more factors than simply the area of land available.

23.9 Conclusions
Sugarcane is one of the most economically important agricultural commodities. Its high vegetative growth potential makes it a very important biofuel feedstock. There are a host of adverse environmental and social impacts associated with sugarcane, despite its benefits in terms of carbon emissions (assuming no new land clearance). These impacts require a resolution if sugarcane is to be cultivated in a sustainable manner. This will require the co-operation of a wide range of actors and will not be easy to achieve.
24. Sweet sorghum

24.1 Feedstock description
Sorghum, a C4 plant of tropical origin is the fifth most important cereal crop and can be used for green fodder, thatch and silage and the production of syrup and fuel (ethanol). It is grown in 99 countries around the world on 44 million ha, mainly in poor and semi-arid areas which are too dry for maize. Sorghum, compared to other crops is more environmentally friendly from the agronomic point of view [258], particularly because of its relatively low nitrogen needs [259] and water requirements [260, 261].

Sweet sorghum is characterized by high sugar content in the juice of the stalks, mainly sucrose and also fructose and glucose, which can easily produce ethanol used as fuel in vehicles. Sweet sorghum has also been called ‘a camel among plants’ [262] because of its wide adaptability, its resistance to saline-alkaline soils and water-logging. It is for this reason that sweet sorghum has become a very popular energy plant throughout the world.

24.2 Feedstock origin
Sweet sorghum is native of Central eastern Africa and belongs to the botanical family of Poaceae, genus Sorghum, species bicolor (L.) Moench. It is a warm season species, as its C4 photosynthetic pathway suggests. Despite its subtropical origin, it is well adapted to marginal lands in semi-arid and temperate regions, including Africa, India, Latin America and Europe. The tropical origin determines by the way, its climatic requirements. In fact, sweet sorghum is a short-day plant and requires 14 hours of light for floral initiation.

![Figure 24.1. Potential geographical areas for sweet sorghum growth (source: EUBIA, [263])](image-url)
24.3 Environmental and ecological impacts

24.3.1 Crop origin and growth pattern
Sweet sorghum is a grass crop belonging to the genus *Sorghum bicolor* L. Moench which also includes grain and fiber sorghum and is characterized by a high photosynthetic efficiency. Sweet sorghum is often considered to be one of the most drought resistant agricultural crops as it has the capability of remaining dormant during the driest periods [264].

Like other sorghum types, sweet sorghum probably originated from East Africa and spread to other African regions, Southern Asia, Europe, Australia and the United States. Although a native to the tropics, sweet sorghum is well adapted to temperate climates.

The plant grows to a height of from about 120 to above 400cm, depending on the varieties and growing conditions and can be an annual (in Europe) or short perennial crop. More than 125 sweet sorghum germplasm resources have been registered in China [265]. Seeds are typically sown in spring after the rainy season and as soon as the soil temperature remains above 15–18°C. Seed germination takes place within 24h in warm and moist soils, and the time to maturity lies between 90 and 120 days. Although the juice, grain and bagasse from sorghum provide opportunities for many uses, most applications around the world are for syrup and forage.

24.3.2 Energy balance and greenhouse gas impact
According to EUBIA (LAMNET project [263]) the energy inputs for 1 ha of sweet sorghum are 4,850 Mcal/ha while the respective outputs (converting sugars to ethanol & lignocellulosic bagasse to pellets are 31,500 Mcal/ha and 43,500 Mcal/ha, respectively) with a total energy output of 74,500 Mcal/ha.

24.3.3 Impact on habitat & biodiversity
Sweet sorghum is a highly competitive crop and can dominate over many weeds and other plants.

Risks associated with agrochemical use
No significant risks have been reported so far concerning the required use of agrochemicals.

Impact on water courses- fertiliser and nitrates
No significant risks have been reported so far.

Impacts on soil
No significant risks have been reported so far.

By-product impacts
The main product of sweet sorghum is the high sugar content juice which is used for ethanol production. However, several studies indicate that the exploitation of the bagasse for energy purposes brings important added value both in terms of economics and GHG balances. No major risks have been reported so far.
24.4 Production

A sweet sorghum crop is established from seed. The seed can be machine sown. Between 6 and 8 kg of seed is needed to establish a hectare of sweet sorghum. Under optimal conditions they germinate and develop a root and canopy system completely covering the soil within a month. The crop is not photoperiod sensitive and reaches maturity in three to five months. During growth the plants accumulate sugars primarily in their stems. Towards maturity, the relative level of sucrose compared to total sugars increases. At maturity sucrose constitutes more than 70% of the sugars [264].

24.4.1 Crop requirements

Table 24.1 below describes the basic requirements in terms of soil, temperature and water for sweet sorghum plantations

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil quality</td>
<td>acceptable heavy clay or high % of sand</td>
</tr>
<tr>
<td>Soil acidity</td>
<td>PH 4.5 to 8.5</td>
</tr>
<tr>
<td>Soil salinity</td>
<td>better resistance than corn</td>
</tr>
<tr>
<td>Temperature</td>
<td>total accumulated daily temperature from 2,600 °C up to 4,600°C during the growing cycle with minimum germination temperature of 8°C – 10°C</td>
</tr>
<tr>
<td>Water demand</td>
<td>200 m³/t with an average rainfall need of 500 to 600 mm.</td>
</tr>
</tbody>
</table>

24.4.2 Yield

Work presented in the LAMNET project shows that the productivity of sweet sorghum depends largely on:

- climatic condition (temperature, precipitation),
- soil quality,
- cultivated varieties, and
- agronomic practices.

Particularly interesting are varieties developed in China since the year 1970, that show a more equilibrated spread between sugar, starch and lignocellulosic yields:

- Grains ~ 5 t/ha
- Sugar ~ 7.5 t/ha
- Lignocellulosic ~ 14.5 odt/ha

These data are frequently used as base for an economic evaluation of commercial bioenergy schemes. Of course, for large size projects, the same results can also be obtained by the adoption of two sweet sorghum varieties: one presenting a much higher grain yield (i.e. hybrid Rio & Soave: ~ 8 t/ha) combined with others presenting higher sugar & lignocellulosic yields.

A typical biomass distribution comprises of:

- Cane: up to 75 % of its weight
- Leaves: 10 – 15 % of its weight
- Grains: up to 7 %
- Roots: ~ 10%
For German High Latitude sites (Braunschweig: 52° 17’ 35’’ North) sweet sorghum Korall varieties, developed by KWS Co., since 1982 were able to produce 20 d.t/ha with an accumulated solar radiation of 500 MJ/m² (as in Grignon, France).

The USA plantations between 21° and 47° latitude yield between 50 to 90 tons (fresh)/ha with sugar yields from 4 to 17 tonnes/ha.

24.4.3 Agrochemical applications
In dry land, seeds are normally sown like corn in rows 75-100 cm apart (distance 14-30 cm on the row) at a rate of 3-9 kg per ha; higher seed rate is used for more humid soils. In good rain fall or very humid irrigation conditions, seeds at 20-25 kg/ha can be used to reduce the big stalk size and to increase the number of leaves. Sorghum hybrids are rather sensitive to low pH and low P and K fertilisation levels. In general fertilisers inputs for Europe are: 30-60 kg/ha of P, 60-120 kg/ha of K, 150 kg/ha of N.

Proposed agronomic regime for modelling purposes
- Soil preparation
- Fertilisation
- Seeding
- Weeding
- Pesticides
- Irrigation
- Harvesting

24.5 Economics
Sweet sorghum is not currently grown at commercial level for ethanol production. The production costs have been estimated in several reports/papers (based on small-to-medium field trials) and range from £500-£700/ha/year dependant on yields & region. In Europe a key element to the production cost is the requirement for irrigated land and water.

24.6 Social context
Farmers’ perception is positive as the crop resembles sugarcane & corn so no additional investment is required for its cultivation.

24.7 Status & prospects
In general, it was almost unanimously recognized that sweet sorghum has a considerable potential as a pro-poor energy crop, not just as a multi-purpose crop in its own right, but also in comparison with sugarcane [266]. The following characteristics are especially noteworthy:
- Sweet sorghum (SS) is an efficient converter of solar energy, as it requires low inputs and yet, a high carbohydrate producer.
- As a drought-tolerant crop with multiple uses, it is particularly important for farmer in fragile agro-economic conditions.
• It has a concentration of sugar which varies between 12-21%, directly fermentable (i.e. no starch to convert).
• It can be cultivated in temperate, subtropical and tropical climates.
• All components of the plant have economic value - the grain from sweet sorghum can be used as food, the leaves for forage, the stalk can be used (along with the grain) for fuel, the fiber(cellulose) either as mulch or animal feed and, with second generation technologies, even for fuel.
• The bagasse, after sugar extraction, has a higher biological value than the bagasse from sugarcane, when used as forage for animals.
• Its growing period is shorter (3-5 months) than that of sugarcane (10-12 months), and the quantity of water required is 1/3.
• In tropical irrigated areas SS can be harvested twice each year (by ratooning) and its production can be labour-intensive or completely mechanized.

24.8 Constraints
The crop is not adapted to the UK climate and pre-processing and transport are not well developed at this stage
25. Cynara cardunculus

25.1 Feedstock description
Cynara cardunculus L. is a perennial herb native to the Mediterranean region, grown since ancient times as a vegetable using intensive management techniques. The adult plant of C. cardunculus in its natural growth cycle exhibits vigorous growth; a single plant can reach a height of 3m and spread over an area of 1.5m in diameter. Its growth pattern and good adaptability to Mediterranean climates suggested it is a species which could be useful for biomass production. Studies of the potential of C. cardunculus for biomass production started in the 1980’s [267, 268].

25.2 Feedstock origin
Cardoon is a member of the daisy family (Compositae) along with sunflower and artichoke. It is a perennial plant originating from the Mediterranean region but has naturalized to parts of Central and South America, and California.

The growth cycle of cardoon (Cynara cardunculus L.) is well adapted to the particular rainfall regime of the Mediterranean region: rainfalls are mostly concentrated on autumn and spring, and there is a long drought period in summertime. Cardoon overcomes the drought period by drying up its aboveground biomass. The natural life form of the plant is as follows:

- It sprouts from stump in autumn giving rise to a leaf rosette that grows steadily during winter and early spring; in mild weather conditions, the plant develops a floral scape that holds several heads of flowers.
- While the seeds ripen –about July- the aboveground biomass dries up; however, the roots remain alive. Then, in summertime, it is time to harvest.
- Afterwards, as soon as the first rains fall –September or October- the latent buds in the plant stump sprout and a new growth cycle starts.
- The life span of cardoon, grown as an energy crop with annual harvests of its aboveground biomass, is still unknown. So far, it has been revealed longer than 12 years.

25.3 Environmental and ecological impacts

25.3.1 Impact on habitat & biodiversity
Wide spacing of lines and high nutrient levels make weed competition a problem for establishing plants. Herbicides can be used to combat this, however, widely separated lines allow weeds to be controlled with a cultivator until the leaf rosettes out compete weeds for light. In subsequent years, once roots are established the plants will immediately dominate weeds [269].

Cardoon in its native regions does have a variety of pests including aphids, stem and leaf borers and miners, cutworms, flies and moths. These can be treated with insecticides and biological controls.
25.3.2 Impacts on soil
It has been reported [270] that cardoon with its robust rooting system can offer protection from soil erosion on the hilly, semi-arid and sloping regions, especially of southern EU.

25.3.3 By-product impacts
Cardoon can be used as a multipurpose crop: its seeds are a good feedstock for biodiesel, the remaining biomass can be used as fuel for heat & electricity (although attention should be paid to high ash content and recent literature suggests that a safe way is to use it in blends with woody biomass types). Further to this the option of receiving fodder (subsequent winter harvests) and biomass has been evaluated and shown good prospects [269].

25.4 Production

25.4.1 Yield
It is well known that one of the most limiting factors for plant growth in the Mediterranean region, when the crop is grown in rainfed conditions, is the precipitation. Consequently, the biomass yields of cardoon are closely related to the precipitation during the respective production year. Studies conducted within the framework of R&D European projects showed that the biomass production of cardoon ranges from 10 to 20 odt/ha/year if the crop is well established and rainfall is about 500mm/year [269, 271]. Productions over 30 odt/ha/year were reached and reported in some cases [269-273]. On average, yields obtained in European experiments range from 7-33 odt/ha/year depending on region, rainfall and year. During a 10-year experiment of cardoon grown in central Spain as a perennial crop under rainfed conditions, the annual productivity ranged from 3.4 odt/ha/year (280mm rainfall year) to 25.2 odt/ha/year (765mm rainfall year); the 10-year average yield was 14 odt/ha/year (470mm rainfall) [274]. Studies on cardoon and water issues have been carried out by Verissimo and Verissimo and Fernandez [275, 276]. The biomass partitioning into leaves, stalk and heads depends on the yield. As a general trend, the higher the yield, the higher the stalk proportion. Seeds represent 8–10% of the aboveground biomass.

25.4.2 Agrochemical applications
As a perennial crop, basal dressing before sowing is recommended. Basal dressing should be applied before ploughing so that the fertilizer is incorporated more deeply as cardoon develops a very deep root system. The fertilizer rates should be applied according to the specific characteristics of the soil, to be determined by soil sampling. As the crop is a great biomass producer, high fertilizer rates might be needed. For low-fertility soils (the conditions of central Spain) about 1000 kg/ha (9:18:27) complex fertilizer are recommended.
From the second year onwards, restoration fertilization is needed to return to the soil the nutrients removed by the crop. Fertilizers rates should be estimated according to the biomass yield obtained in the harvest. Studies conducted in Spain have shown an uptake rate of 12.6 kg N, 3.5 kg P2O5 and 20.8 kg K2O/t per oven-dry matter biomass [274]. The restoration fertilization can be either performed in winter or spring but an annual soil nutrient surveillance is recommended.

25.4.3 Proposed agronomic regime for modelling purposes

The costs for the plantation lifetime can be divided in establishment and recurring ones.

**Establishment:** ploughing, harrowing, herbiciding, fertilising, sowing, initial irrigation, exit costs.

**Annual costs:** land rent, fertilisation, harvesting, other costs (material inputs).

25.5 Economics

The economic calculations from Spain indicate costs of cardoon as delivered to the energy plant of about 24 ECU/odt (remark: data of 1996).

The low costs are due to low establishment costs, low input of fertilizer and irrigation and a high yield. Respective costs in Greece reach 744 €/ha/year or 41.3 €/t (2.5 €/GJ) with an average yield of 18 odt/ha/year. [277].

Table 25.1 Establishment and recurring costs for cardoon (€/ha/year)

<table>
<thead>
<tr>
<th>Planted Lifetime</th>
<th>Cardoon</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td></td>
</tr>
<tr>
<td><strong>Establishment costs</strong></td>
<td></td>
</tr>
<tr>
<td>€/ha</td>
<td>%</td>
</tr>
<tr>
<td>Ploughing</td>
<td>130</td>
</tr>
<tr>
<td>Harrowing</td>
<td>130</td>
</tr>
<tr>
<td>Herbiciding</td>
<td>130</td>
</tr>
<tr>
<td>Initial fertilising</td>
<td>63</td>
</tr>
<tr>
<td>Sowing</td>
<td>200</td>
</tr>
<tr>
<td>Initial irrigation</td>
<td>38</td>
</tr>
<tr>
<td>Exit costs (Grubbing up)</td>
<td>142</td>
</tr>
<tr>
<td>(a) Total Establishment costs</td>
<td>833</td>
</tr>
<tr>
<td>(b) Annual equivalent of establishment costs</td>
<td>113</td>
</tr>
<tr>
<td><strong>Recurring costs (in all years ex. Harvesting)</strong></td>
<td></td>
</tr>
<tr>
<td>Land rent</td>
<td>120</td>
</tr>
<tr>
<td>Fertilisation</td>
<td>73</td>
</tr>
<tr>
<td>Harvesting</td>
<td>86</td>
</tr>
<tr>
<td>Cost of working capital</td>
<td>151</td>
</tr>
<tr>
<td>Other costs (incl. depreciation of travelling gun)</td>
<td>201</td>
</tr>
<tr>
<td>(c) Total recurring costs</td>
<td>631</td>
</tr>
<tr>
<td><strong>Total annual equivalent cost (b+c)</strong></td>
<td>744</td>
</tr>
<tr>
<td><strong>Cost (€/odt)</strong></td>
<td>41.3</td>
</tr>
</tbody>
</table>

In cost analysis the establishment costs are annualised and the annual equivalent \( e = c_i / \left(1 - (1 + i)^{-n}\right) \), where \( c_i = \) purchase cost, \( i = \) discount rate and \( n = \) item lifespan is added to the recurring costs in order to estimate the total annual equivalent cost.

\( ^9 \) Average yield of 18 odt/ha/year
25.6 Social context
Although perennial, cardoon is easy to clear if compared to grasses with rhizomes or trees. This along with the fact that it is a rainfed high yield crop increases positive perception among farmers.

25.7 Status & prospects
Cardoon seems to be well adapted to the dry Mediterranean conditions where most precipitation occurs during the winter season. It can therefore produce high yields without irrigation and complement crops like miscanthus, sorghum and giant reed in a year round crop system. The possibility of harvesting the crop for fodder increases its value at the farm level. As the harvest and use of the crop is not well developed, this should be given high priority in order to evaluate the whole bioenergy chain of the crop and its possibilities for future biorefineries.
26. Olive residues

26.1 Feedstock description
The olive, *Olea europaea* L., is a subtropical evergreen tree or shrub that has been known to live for more than 1,000 years. Olives will bear fruit on average after 5 years, and it is the most extensively cultivated fruit crop in the world [278]. It is cultivated throughout the Mediterranean basin and in the southern United States. Olive oil and table olives are the primary products from the cultivation of olives. Until recently residues from olive plantations were rarely used as a renewable energy source, and traditionally only the olive kernels were used for combustion [279]. In the UK, olive residues are one of the most common products for biomass co-firing and, in 2005, 283,222 tonnes were used for co-firing [225].

26.2 Feedstock origin
The olive is thought to have originated from the Syrian/ Iranian region from where its cultivation spread, at a very early period, to other areas of the Mediterranean basin. The history of olive cultivation in the Mediterranean can be traced back more than 8,000 years, and olives have long been recognised as an important part of both Greek and Roman mythologies [280].

26.3 Production
A practical guide to olive cultivation is available from the EC Olive Technology Dissemination Centre [281]. Around 80% of olives are cultivated in the Mediterranean basin, with Spain the biggest producer cultivating more than 2.4 million hectares in 2005. 97% of global production of olive oil occurs in the Mediterranean basin [282]. Olives are grown in monocultures and have annual yields that range from 500 to 10,000 kg olives per hectare [225]. In Spain, irrigated olive groves can produce an olive yield 3-4 times that of unirrigated groves [283], and variation in seasonal rainfall has historically been a major determinant of yield [284]. Due to the high variation between locations and seasons, a typical yield is not straightforward to define, but, by way of illustration, Vossen [284] refers to the best olive orchards in Catalunya as producing 2-4 tons per acre per year (depending on irrigation), which equates to 1.8 - 3.6 tonnes per 0.41ha, i.e. about 4.4 – 8.8t/ha. Perhaps a typical yield might therefore be nominally defined as 5t/ha/yr? Global production of crude olive cake is unsurprisingly dominated by the Mediterranean countries; an estimated 5 million tonnes (Mt) are produced globally with more than 3Mt produced by Spain, Italy and Greece (ibid).

Climate is a limiting factor in the cultivation of olives, with temperature controlling growth, reproduction and survival. Olive trees grow on well drained soils although they may require irrigation. Olives are drought tolerant due to their small, waxy leaves and slow transpiration. It is tolerant of mild salinity and grows in soils with up to pH 8.5. Fertilisers may occasionally be used to increase yield. Olive trees suffer from fewer pests and diseases than most fruit trees and, as a result, are one of the least sprayed crops. Two major Mediterranean pests are the medfly and the olive fruit fly, *Dacus oleae*, while in the US verticillum wilt is a series fungal disease [278].

Olive residues are the by-products from the production of olive oil and consist of the crushed olive kernel, skin, cuttings, shell, pulp, water and residual oil. The amounts
of waste produced depend on the system of extraction. Table 26.1 details the percentages of by-products associated with different extraction methods.

**Table 26.1** Percentages of by-products corresponding to different oil extraction technologies

<table>
<thead>
<tr>
<th>Technology</th>
<th>Input</th>
<th>Amount of input (t)</th>
<th>Output</th>
<th>Percentage of output/ olives</th>
</tr>
</thead>
<tbody>
<tr>
<td>Presses</td>
<td>Olives, Olive husks (OH), Oil mill wastewater (OMW)</td>
<td>1, 20</td>
<td>Oil, OH</td>
<td>20, 40</td>
</tr>
<tr>
<td>Three-phase decanter</td>
<td>Olives, Water</td>
<td>1, 1</td>
<td>Oil, OMW</td>
<td>20, 50</td>
</tr>
<tr>
<td>Two-phase decanter</td>
<td>Olives, Sludge</td>
<td>1</td>
<td>Oil, Sludge</td>
<td>20, 80</td>
</tr>
</tbody>
</table>

From: [285]

Traditionally, residues were used as a low value animal feed or fertiliser, and were considered problematic for disposal. More recently, olive residues are being used by olive processing plants as a source of heat for processing, or for activated carbon production. Residues are good for co-firing as they can be easily co-milled; they may be imported as cake, expeller or pellets. The physical and energy properties of olive residues will vary according to the processing method used [225]. Table 26.2 shows the residue, treatment method and potential end use of different components of olive residues.

**Table 26.2.** Final product uses of selected olive residues, with treatment methods

<table>
<thead>
<tr>
<th>Residue</th>
<th>Treatment method</th>
<th>Final product/ uses</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solid wastes</td>
<td>Pyrolysis at 550°C</td>
<td>Soil stabiliser</td>
</tr>
<tr>
<td>Olive pit and cuttings</td>
<td>Pyrolysis at 400-700°C with heating rates 120–165°C s⁻¹ at atmospheric pressure, under nitrogen</td>
<td>Charcoal briquetting; use as bio-oil needs to be investigated</td>
</tr>
<tr>
<td>Olive residues</td>
<td>Pyrolysis in a stainless steel fixed bed reactor (400-700°C) under different atmospheres</td>
<td>Fuel and chemical feedstock</td>
</tr>
<tr>
<td>Olive bagasse</td>
<td>Pyrolysis in a stainless steel tubular reactor with a sweep gas (nitrogen) at 350–550°C</td>
<td>Fuel and chemical feedstock</td>
</tr>
<tr>
<td>Olive mill wastewater</td>
<td>Evaporated (under vacuum or atmospheric pressure), dried at 105 °C, and pyrolysed (200–550°C)</td>
<td>Fuel to provide heat in the evaporation stage</td>
</tr>
<tr>
<td>Olive husk</td>
<td>Direct and catalytic (ZnCl₂, Na₂CO₃, K₂CO₃) pyrolysis (477–752°C) in a stainless steel cylindrical reactor</td>
<td>Fuel for internal combustion engines</td>
</tr>
<tr>
<td>Solid wastes</td>
<td>Combustion (average temperature 850 ± 10°C, combustion air temperature 23°C, flow of combustion air 570 Nm³ h⁻¹ and relative humidity 40%)</td>
<td>Substitute for No.2 heavy fuel</td>
</tr>
<tr>
<td>Olive cake</td>
<td>Drying in oven (1 h, 105–110°C), grounded in a mill (reduction particle size) and mixture with oil shale</td>
<td>Energy production</td>
</tr>
<tr>
<td></td>
<td>Combustion in a circulating fluidised bed (900°C–5 h)</td>
<td>Fuel in small scale industries</td>
</tr>
<tr>
<td></td>
<td>Co-combustion with lignite coal in a circulating fluidised bed (700°C)</td>
<td>Energy production</td>
</tr>
</tbody>
</table>
Co-combustion with lignite coal in a circulating fluidised bed (700°C) Treatment of metal bearing effluents

Energy production

Treated olive mill residues Dried, ground and sieved Gasification/combustion Energy production

Olive mill wastewater/olive husk Transesterification with methanol in presence of KOH (catalyst)

Biodiesel fuel production

From: [286]
Attom and Al-Sharif [287] give the chemical composition of burned olive waste, by weight using a flame photometer and spectrophotometer, as:

<table>
<thead>
<tr>
<th>Element</th>
<th>Percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>P</td>
<td>0.275</td>
</tr>
<tr>
<td>Na</td>
<td>0.077</td>
</tr>
<tr>
<td>Ca</td>
<td>2.063</td>
</tr>
<tr>
<td>K</td>
<td>1.10</td>
</tr>
</tbody>
</table>

García-Ibañez et al [288] state that the dry solid olive waste “orujillo”, arising from the final stage of processing, has a heating value of approximately 17,000 kJ/kg and a moisture level of 8–10%. García-Ibañez et al [288] provide further detail on chemical composition as in Table 26.3 below.

Table 26.3 Leached orujillo characteristics [288]

<table>
<thead>
<tr>
<th>Analytical data</th>
<th>Ash Analysis (wt%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moisture content (wt %)</td>
<td>8.9</td>
</tr>
<tr>
<td>Bulk density (kg/m³)</td>
<td>659</td>
</tr>
<tr>
<td>Average particle size (mm)</td>
<td>1.89</td>
</tr>
<tr>
<td>Proximate (wt%, dry basis)</td>
<td>MgO 12.86</td>
</tr>
<tr>
<td>Volatile matter</td>
<td>74.4</td>
</tr>
<tr>
<td>Fixed carbon</td>
<td>17.1</td>
</tr>
<tr>
<td>Ash</td>
<td>8.5</td>
</tr>
<tr>
<td>Ultimate (wt%, daf basis)</td>
<td>Fe₂O₃ 2.37</td>
</tr>
<tr>
<td>C</td>
<td>52.7</td>
</tr>
<tr>
<td>H</td>
<td>7.2</td>
</tr>
<tr>
<td>N</td>
<td>1.6</td>
</tr>
<tr>
<td>S</td>
<td>0.07</td>
</tr>
<tr>
<td>Cl</td>
<td>0.37</td>
</tr>
<tr>
<td>O (diff)</td>
<td>38.1</td>
</tr>
<tr>
<td>HHV (MJ/kg)</td>
<td>19.9</td>
</tr>
<tr>
<td>LHV (MJ/kg)</td>
<td>18.5</td>
</tr>
</tbody>
</table>

26.4 Economics and trade

EU legislation is a key driver of the economics of the use of waste products for energy. However, although there are various processes available for the disposal of olive residues, Celma et al [285] argue that the economic profitability of these processes is uncertain, even when the reduced environmental impacts associated with their treatment are taken into account. As a result, there is growing interest in adding value to these residues by using them to produce energy.
Unlike PKE, international trade statistics distinguish between olive residues that are likely to be used for energy and those that are not. Dry olive cake, a residue suitable for energy use, contains 3% olive oil or less. Large imports of olive cake did not begin until 2003, when around 11,000 tonnes were imported into the UK; by 2005, this had increased to more than 172,000 tonnes. The UK is Europe’s largest importer of dry olive cake, accounting for 55% of imports [225]. Woods et al (ibid: 43) predict that due to the low value of olive residues, large quantities will become available if a large scale market for their use as an energy source develops.

### 26.5 Environmental and ecological impacts

The environmental impacts of olive plantations have been less studied than other agricultural systems in the EU, although the treatment of waste from the olive industry has seen a flurry of research in recent years. There are considerable negative environmental impacts associated with the production and processing of olives including soil erosion, pruning and processing waste residues, run-off to water bodies, use of agrochemicals, degradation of habitats and landscapes, and exploitation of water resources [289]. In addition, olive processing plants produce highly polluted waste water and/ or a solid residue depending on the oil extraction method used. Approximately, 10 million metre$^3$ of olive mill waste water are produced annually in the Mediterranean region. This liquid residue has a high organic load, which can cause eutrophication particularly in water bodies where exchange rates are low [280, 286]. Furthermore, there are significant emissions are associated with the production and processing of olives [282]. Olive waste can also be a problem simply by virtue of its substantial mass [287] (see remediation methods below).

As may be expected, the environmental impacts of olive farming vary according to the region, as well as on the physical characteristics of the plantation, management practices and socio-economic practices. Beaufoy [289] identifies three types of plantation:

1. **Traditional plantations:** low input plantations with scattered trees, some of which may be ancient. Managed with few or no chemical inputs but have a high labour input.

2. **Intensified traditional plantations:** Follow traditional methods to a lesser extent, these plantations are under more intensive management and use larger amounts of chemical inputs. Irrigation, increased tree intensity and mechanical harvesting may be used.

3. **Intensive modern plantations:** use smaller tree varieties, planted at high densities. These are intensively managed making use of both irrigation and mechanical harvesting.

Therefore, traditional plantations have the greatest biodiversity benefits as well as fewer environmental impacts. However, they are also the least productive and thus are most vulnerable to abandonment. While, the intensification and expansion of olive production is likely to occur, potentially leading to increased negative environmental impacts, this may potentially be mitigated through appropriate farming practices.

There are a number of methods to treat the waste from olive processing mills including bioremediation, thermal processes, evaporation, membrane processes,
electrolysis, aerobic and anaerobic digestion, ozonation, coagulation/ flocculation/ precipitation, and distillation [280]. There are different environmental impacts associated with the treatment methods; the end products of thermal processing (combustion, pyrolysis and gasification), which may or may not involve energy recovery, are ash, gases such as CO₂ and NOₓ, and water. Thermal treatment of olive residues reduces the environmental impacts in two ways: firstly by detoxifying the hazardous waste; and secondly in converting residues to solids the volume of waste is reduced. However, despite the energy recovery from thermal processing, Arvanitoyannis et al [280], in their review of waste disposal methods, conclude that the most environmentally friendly technique for waste disposal is bioremediation.

26.6 Social context
Within the EU, olive production occurs across a wide range of socio-economic contexts. Olive plantations are an important source of principal and part-time employment in many rural areas of the Mediterranean. In some regions, olive production is the principal economic activity and remains an important part of culture and heritage. However, employment in olive plantations is not secure, and may be low paid and seasonal. In some areas, mechanisation has reduced the need for labour input, while in others ageing populations and emigration have led to a reduced labour force [289]. Attempts to modernise the sector in the EU have been successful in more progressive regions, such as Andalucía, while the growing value of labelling schemes has led to an artisan olive sector in other regions, such as Toscana (ibid). However, in other areas production has stagnated and is kept alive by subsidies leading to a significant risk of abandonment.

With respect to the use of olive residues for energy recovery, most social concerns will relate to public fears about the potential negative health impacts from the incineration of waste. For a more detailed discussion of public concerns about energy recovery from waste, readers are referred to the review of MBT.

26.7 Key constraints
Currently, there are few constraints on the use of olive residues for energy recovery. For every tonne of olive oil produced, on average 0.8 tonnes of residues and wastewater are generated [285]. As stated previously, the disposal of the residues has been long a concern for the industry, as the residues create multiple environmental impacts. As emphasised by Woods et al [225], the low value of olive residues means that large quantities will potentially become available if a large scale market for their use as an energy source develops. World production of crude olive cake is estimated to be 5 Mt, with over 3 Mt coming from Spain, Italy and Greece (ibid). In the medium term, the availability of this resource to the UK is likely to reflect the interaction of transport costs and renewable energy subsidies or carbon emission costs, internationally. Berry et al. [290] show that, with climate change up to 2080, the European extent of the olive-suitable zone will extend in area. However, southwest France, Spain, Portugal and Italy will experience higher temperatures and increased aridity, with a negative effect on farm profitability and abandoned agricultural land becoming widespread in currently marginal areas (ibid).
Key technical constraints of using olive residues vary according to the part of the residue being used. Use of the olive kernels can be problematic due to their resilience, which may cause problems in milling equipment. In addition, olive residues often have high sodium contents (due to pickling in brine), and this can cause corrosion and ash quality problems if fired in high proportions. Less obvious, but no less problematic, is the strong odour of the olive residues, which may occasionally raise objections [291].

It is likely, given the negative environmental impacts of olive residues and difficulties with their disposal, that stakeholders will have few complaints about the use of olive residues for energy recovery. Nonetheless, one possible stakeholder concern may due to the loss of residues as a fertiliser and subsequent loss of minerals and trace metals from the soil. However, the use of olive residues as a fertiliser is low in modern plantations and agrochemicals preferentially used [289]. While this means the impact on soil fertility from the translocation of olive residues is likely to be minimal, it may mean that the emissions associated with production are higher due to the use of artificial fertilisers.
27. Ethanol
Ethanol is included here as a feedstock due to its potential for both domestic production and importation as a refined fuel.

27.1 Feedstock description
Further information on the properties of ethanol can be found at the US DoE Alternative Fuels and Advanced Vehicles Data Centre: http://www.eere.energy.gov/afdc/, on which this section draws. Ethanol (CH$_3$CH$_2$OH; also known as ethyl alcohol, grain alcohol, and EtOH) is a clear, flammable and moderately toxic liquid with a perfume-like smell. Its molecules contain a hydroxyl group (-OH) bonded to a carbon atom C$_2$H$_6$O. Ethanol is a high-octane fuel that has historically been used in high-performance vehicles and to help prevent engine knocking. Low-level blends of ethanol, such as E10 (10% ethanol, 90% gasoline), generally have a higher octane rating than unleaded gasoline. Low-octane gasoline can be blended with 10% ethanol to attain the standard 87 octane requirement [292].

Ethanol is the main component in E85, a high-level blend of 85% ethanol, 15% gasoline. The American Society of Testing and Materials (ASTM) has developed E85 fuel specifications to ensure proper starting, operation, and safety. E85, like gasoline and diesel fuels, is seasonally adjusted to ensure proper starting and performance in different geographic locations. For example, E85 sold during colder months often contains 70% ethanol and 30% petroleum to produce the necessary vapour pressure for starting in cold temperatures. An E85 fuelling site operator typically cannot carry over summer-blend E85, but rather must "blend down" any remaining summer fuel to make an E70 mixture (US DoE, 2007b). Table 27.1 below is a statement of minimum commercial standards developed by The American Society of Testing and Materials (ASTM) for E85 fuel. In the Table, the Value of Class refers to the Volatility Class by a geographic-specific month.

Table 27.1: ASTM Specification for fuel ethanol

<table>
<thead>
<tr>
<th>Property</th>
<th>Value of Class</th>
<th>Test Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>ASTM volatility class</td>
<td>1, 2, 3</td>
<td>N/A</td>
</tr>
<tr>
<td>Ethanol, plus higher alcohols (minimum volume %)</td>
<td>79, 74, 70</td>
<td>ASTM D 5501</td>
</tr>
<tr>
<td>Hydrocarbons (including denaturant) (volume %)</td>
<td>17-21, 17-26, 17-30</td>
<td>ASTM D 4815</td>
</tr>
<tr>
<td>Vapor pressure at 37.8°C kPa psi</td>
<td>38-59, 48-65, 66-83</td>
<td>ASTM D 5191</td>
</tr>
<tr>
<td>Lead (maximum, mg/L)</td>
<td>2.6</td>
<td>ASTM D 5059</td>
</tr>
<tr>
<td><strong>Phosphorus (maximum, mg/L)</strong></td>
<td>0.3</td>
<td>0.3</td>
</tr>
<tr>
<td>--------------------------------</td>
<td>-----</td>
<td>-----</td>
</tr>
<tr>
<td><strong>Sulfur (maximum, mg/kg)</strong></td>
<td>210</td>
<td>260</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Methanol (maximum, volume %)</strong></td>
<td>0.5</td>
<td>N/A</td>
</tr>
<tr>
<td><strong>Higher aliphatic alcohols, C3-C8 (maximum volume %)</strong></td>
<td>2</td>
<td>N/A</td>
</tr>
<tr>
<td><strong>Water (maximum, mass %)</strong></td>
<td>1.0</td>
<td></td>
</tr>
<tr>
<td><strong>Acidity as acetic acid (maximum, mg/kg)</strong></td>
<td>50</td>
<td></td>
</tr>
<tr>
<td><strong>Inorganic chloride (maximum, mg/kg)</strong></td>
<td>1</td>
<td></td>
</tr>
<tr>
<td><strong>Total chlorine as chlorides (maximum, mg/kg)</strong></td>
<td>2</td>
<td></td>
</tr>
<tr>
<td><strong>Gum, unwashed (maximum, mg/100 mL)</strong></td>
<td>20</td>
<td></td>
</tr>
<tr>
<td><strong>Gum, solvent-washed (maximum, mg/100 mL)</strong></td>
<td>5.0</td>
<td></td>
</tr>
<tr>
<td><strong>Copper (maximum, mg/100 mL)</strong></td>
<td>0.07</td>
<td></td>
</tr>
<tr>
<td><strong>Appearance</strong></td>
<td>Product shall be visibly free of suspended or precipitated contaminants (shall be clear and bright).</td>
<td>Appearance determined at ambient temperature or 21°C (70°F), whichever is higher.</td>
</tr>
</tbody>
</table>

N/A = Not applicable

**27.2 Feedstock origin**

Ethanol is a refined fuel produced from a variety of feedstocks as described below. Many countries have implemented or are implementing programs for addition of ethanol to gasoline, with world ethyl alcohol production in 2006 being 51,000 million litres (Renewable Fuels Association, 2007, in [293]). The USA and Brazil are the largest producers, at 18,376 and 16,998 million litres respectively in 2006, with the next largest producer being China at 3,849 million litres, and India fourth at 1,900 million litres. In 2006 the UK was the twelfth largest producer of ethanol, at 280 million litres (ibid). Approximately 73% of Brazilian sugarcane production is concentrated in the state of São Paulo (Braunbeck et al, 1999, in [294]).
27.3 Production

Sánchez and Cardona [293] describe the different technologies for producing fuel ethanol from sucrose-containing feedstocks (mainly sugar cane), starchy materials and lignocellulosic biomass, along with the major research trends for improving them. Fuel ethanol can be obtained from energy crops and lignocellulosic biomass, using technologies that range from the simple conversion of sugars by fermentation, to the multi-stage conversion of lignocellulosic biomass into ethanol (ibid).

In ethanol production from sugar, the micro-organism most commonly used is *Saccharomyces cerevisiae* due to its capability to hydrolyze cane sucrose into glucose and fructose, two easily assimilable hexoses. Aeration is an important factor for growth and ethanol production by *S. cerevisiae*. Although this microorganism has the ability to grow under anaerobic conditions, small amounts of oxygen are needed for the synthesis of substances like fatty acids and sterols. The oxygen may be supplied through the addition to the medium of some chemicals like urea hydrogen peroxide (carbamide peroxide) (ibid).

The *Melle-Boinot* process is that typically used for fuel ethanol production by batch fermentation. This process consists of weighing and sterilizing the feedstock, followed by the adjustment of pH with H$_2$SO$_4$ and of the degrees Brix (a measurement of the mass ratio of dissolved sucrose to water in a liquid) to values of 14–22. The resultant wort (mash) is then fermented by yeasts. The wine produced from the fermentation process is decanted, centrifuged and sent to an ethanol separation stage, whereas the yeasts are recycled to the fermentation process (ibid). In the case of multiple or repeated batch fermentation, the use of flocculating yeast strains plays an important role (ibid). However, the design and development of continuous fermentation systems has allowed the implementation of more cost-effective processes. Continuous processes have several advantages compared to conventional batch processes, notably the reduced construction costs of the bioreactors, lower maintenance and operation requirements, better process control, and higher productivities (ibid).

Starch is potentially a high yield feedstock for ethanol production, but its hydrolysis is required to produce ethanol by fermentation. Starch was traditionally hydrolyzed by acids, but the specificity of the enzymes, their inherent mild reaction conditions and the absence of secondary reactions have led to the amylases to be the catalysts generally used for this process (ibid). α-amylase obtained from thermo-resistant bacteria such as Bacillus licheniformis or from engineered strains of Escherichia coli or Bacillus subtilis is used during the first step of hydrolysis of starch suspensions. For amylases to attack starch, these suspensions need to be brought to high temperatures (90–110 °C) for the breakdown of starch kernels. More recently, the possibility of hydrolyzing starch at low temperatures for achieving energy savings is being investigated [295]. The product of this first step, called liquefaction, is a starch solution containing dextrines and small amounts of glucose. The liquefied starch is subject to saccharification at lower temperatures (60–70 °C) through glucoamylase obtained generally from Aspergillus niger or Rhizopus species ([296] and [297] in [293]).

Ethanol is produced almost exclusively from corn in the USA. Corn is milled to extract the starch, which is enzymatically treated to obtain a glucose syrup. Then, this
syrup is fermented into ethanol. There are two types of corn milling used in the industry: wet and dry. During wet-milling process, corn grain is separated into its components. Starch is converted into ethanol and the remaining components are sold as co-products. During dry-milling, grains are not fractionated and all their nutrients enter the process and are concentrated into a distillation co-product called Dried Distiller’s Grains with solubles (DDGS), which is used for animal feed. In general, the liquefaction, saccharification and fermentation steps are the same for both technologies. Fermentation is performed using \textit{S. cerevisiae} and is carried out at 30–32 °C with the addition of ammonium sulfate or urea as nitrogen sources. [293].

Ethanol produced from wheat and other starchy crops uses methods that are in essence similar, but which often entail specific variants in method (ibid). For example, ethanol production from cassava may entail starch extraction through a high-yield large-volume industrialized process as the Alfa Laval extraction method [298] in [293], or by a traditional process for small- and mid-scale plants. The latter process can be considered equivalent to the wet-milling process for ethanol production from corn (ibid).

The significance of \textit{lignocellulosic biomass} as a feedstock for ethanol production can be inferred from its prevalence. Lignocellulosic complex is the most abundant biopolymer on Earth and comprises about 50% of world biomass (ibid). In general, prospective lignocellulosic materials for fuel ethanol production can be divided into six main groups:

- crop residues (e.g. cane bagasse, corn stover, wheat straw, rice straw, rice hulls, barley straw, sweet sorghum bagasse, olive stones and pulp)
- hardwood (e.g. aspen, poplar)
- softwood (e.g. pine, spruce)
- cellulose wastes (e.g. newsprint, waste office paper, recycled paper sludge)
- herbaceous biomass (e.g. alfalfa hay, switchgrass, reed canary grass, coastal Bermuda grass, timothy grass) and
- municipal solid wastes (MSW) (ibid).

The main processing challenge in the ethanol production from lignocellulosic biomass is the feedstock pre-treatment (ibid). The lignocellulosic complex is made up of a matrix of cellulose and lignin bound by hemicellulose chains. During the pretreatment, this matrix needs to be broken to reduce the crystallinity of the cellulose and increase the fraction of amorphous cellulose, the most suitable form for enzymatic attack. Additionally, main part of hemicellulose should be hydrolyzed and lignin should be released or even degraded. The fact that the cellulose hydrolysis is affected by the porosity (accessible surface area) of lignocellulosic materials is also relevant. The yield of cellulose hydrolysis is less than 20% of the theoretical when pretreatment is not carried out, whereas the yield after pretreatment often exceeds 90% of theoretical ([293]).

Sánchez and Cardona [293] describe the process of breaking lignocellulosic biomass into fermentable sugars as “complicated, energy-consuming and non-completely developed”. The main processes are described here in order to convey something of their complexity and something of the problems involved. In summary, Sánchez and Cardona [293] list \textit{pre-treatment methods} for the production of lignocellulosic ethanol as follows.
• *Physical methods*: waste materials can be comminuted by a combination of chipping, grinding and milling to reduce cellulose crystallinity.

• *Physical–chemical methods*: considerably more effective than physical. The steam explosion is the most studied method of this type. During this process, the use of saturated steam at high pressure causes autohydrolysis reactions in which part of the hemicellulose and lignin are converted into soluble oligomers. One of the most promising methods is the pretreatment with Liquid Hot Water (LHW) or thermohydrolysis.

• *Chemical methods*: these employ different chemical agents as ozone, acids, alkalis, peroxide and organic solvents. Inorganic acids as H$_2$SO$_4$ and HCl have been preferably used for biomass pretreatment. Hydrolysis with dilute sulphuric acid has been successfully developed given that high reaction rates can be achieved improving significantly the subsequent process of cellulose hydrolysis. Dilute acid pretreatment along with steam explosion is one of the most widely studied methods, though concentrated acids also have been used for pre-treatment, and alkaline pretreatment is based on the effects of the addition of dilute bases on the biomass.

• *Biological pre-treatment*: this method has low energy requirements and mild environmental conditions. However, most of these processes are too slow limiting its application at industrial level. Many white-rot fungi degrade the lignin and, for this reason, they have been utilized for ligninases production and lignocellulose degradation.

Subsequent to pre-treatment, further processing stages are required to convert lignocellulosic biomass to ethanol. The next stage, a subject of intensive research, is detoxification of lignocellulosic hydrolyzates, as during pretreatment and hydrolysis of lignocellulosic biomass, large quantities of compounds that can seriously inhibit the subsequent fermentation are formed in addition to fermentable sugars (ibid). Following this, the cellulose should be degraded into glucose (saccharification) using acids or enzymes. In the former case, concentrated or dilute acids can be used. If dilute acids (H$_2$SO$_4$ and HCl) are employed, temperatures of 200–240 °C at 1.5% acid concentrations are required to hydrolyze the crystalline cellulose. However, cellulose hydrolysis is also currently carried out using microbial cellulolytic enzymes. Enzymatic hydrolysis has demonstrated better results for the subsequent fermentation because no degradation components of glucose are formed although the process is slower.

The next stage is the fermentation of biomass hydrolyzates. This may be carried out as a sequential process in which the hydrolysis of cellulose and the fermentation are carried out in different units. This configuration is known as separate hydrolysis and fermentation (SHF). In the alternative variant, the simultaneous saccharification and fermentation (SSF), the hydrolysis and fermentation are performed in a single unit. One of the main problems in bioethanol production from lignocellulosics is that *S. cerevisiae*, the yeast most commonly used in fermentation, can ferment only particular mono- and disaccharides such as glucose, fructose, maltose and sucrose.
This microorganism is not able to assimilate cellulose and hemicellulose directly. In addition, pentoses obtained during hemicellulose hydrolysis (mainly xylose) cannot be assimilated by this yeast. One way to overcome this obstacle may be through recombinant DNA technology (genetic engineering), or the use of pentose fermenting microorganisms like some species of yeasts and bacteria. In this case, configurations involving the separate fermentation of pentoses and hexoses have been proposed. Yeasts as *Pichia stipitis*, *Candida shehatae* and *Pachysolen tannophilus* can assimilate pentoses but their ethanol production rate from glucose is at least five times less than that observed for *S. cerevisiae*. Moreover, their culture requires oxygen and ethanol tolerance is 2-4 times lower (ibid).

### 27.4 Economics

Sánchez and Cardona ([293]Table 7) summarise the costs and yields of the main ethanol feedstocks. The potential advantages of lignocellulosic materials for ethanol production are their output/input energy ratio, their great availability both in tropical and temperate countries, their low cost (primarily related to their transport), their ethanol yields and their potentially not competing with food production (i.e. if they are a waste) and their potential to be processed in different ways for products such as synthesis gas, methanol, hydrogen and electricity (ibid). Sánchez and Cardona (ibid) state that for the USA, corn stover is considered one of the most promising feedstocks due to its wide availability. The total availability of this material in the United States in such a way that its recollection and use be environmentally sustainable, has been estimated in about 80–100 mill dry ton per year. Other studies point to the potential of rice straw for ethanol production [293].

Selected extracts from the summary of ethanol feedstock performance by Sánchez and Cardona (ibid, Table 7) are given in Table 27.2 below. However, it is important to note that the energy output/input ratio will be highly dependent on specific assumptions, particularly the co-production of additional outputs. Even with the same system assumptions, a range of values for the same parameters can be found in the literature. Oliveira et al ([294]: 596) found that, for Brazilian ethanol production and using values in the literature, assuming a scenario with a sugarcane yield of 69 Mg per ha, rather than 80 Mg per ha, an ethanol conversion rate of 80 liters per Mg of sugarcane instead of 85 liters, and an energy requirement of 75.6 GJ to produce 1 Mg of N instead of 57.5 GJ, produced a difference in energy balance of about 23%. Less significant variations were observed for variables in corn ethanol production in the United States. For example, the difference in energy balance between best- and worst-case scenarios was only about 9% for corn ethanol production (ibid: 596).
**Table 27.2 Selected aspects of ethanol feedstock performance (edited from Sánchez and Cardona, [293], Table 7)**

<table>
<thead>
<tr>
<th>Property</th>
<th>Sucrose-containing materials</th>
<th>Starchy materials</th>
<th>Lignocellulosic biomass</th>
<th>Feedstock type</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feedstock cost, US$/kg</td>
<td>0.0100</td>
<td></td>
<td>Sugar cane; Brazil</td>
<td>Macedo and Nogueira (2005)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.0760</td>
<td></td>
<td>Corn; USA</td>
<td>McAloon et al. (2000)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.0124</td>
<td>0.1300</td>
<td>Cane/corn; Colombia</td>
<td>Quintero et al. (2007)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Dry corn stover, USA</td>
<td>Aden et al. (2002)</td>
<td></td>
</tr>
<tr>
<td>Production costs, US$/L anhydrous EtOH</td>
<td>0.1980</td>
<td></td>
<td>Sugar cane; Brazil</td>
<td>Xavier (2007)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.2153</td>
<td>0.3381</td>
<td>Sugar cane/corn; Colombia</td>
<td>Quintero et al. (2007)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0.2325</td>
<td>0.3963</td>
<td>Corn/corn stover; USA</td>
<td>McAloon et al. (2000)</td>
<td></td>
</tr>
<tr>
<td>Output/input energy ratio</td>
<td>8.0</td>
<td></td>
<td>Sugar cane</td>
<td>Berg (2001)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.34–1.53</td>
<td></td>
<td>Sugar beet</td>
<td>Berg (2001), Shapouri et al. (2003)</td>
<td></td>
</tr>
<tr>
<td>Annual EtOH yield, L/(Ha year)</td>
<td>5,345–9,381</td>
<td>Sugar cane; Brazil, Colombia</td>
<td>Agrocadenas (2006), Asocaña (2006)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>6,600</td>
<td></td>
<td>Sugar beet; France</td>
<td>Poitrat (1999)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3,600</td>
<td></td>
<td>Cassava</td>
<td>Agrocadenas (2006)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>9,030</td>
<td></td>
<td>Sweet sorghum</td>
<td>Agrocadenas (2006)</td>
<td></td>
</tr>
</tbody>
</table>
27.5 Environmental and ecological impacts

The principal ways of conceiving of and measuring environmental impact are (a) with respect to geographic locations (notably, but not only, sites of agricultural production and processing plant) and (b) in terms of parameters that can be aggregated over the life cycle of the production process, via LCA methods. The latter generally do not capture all site-specific impacts; while LCA does capture pollutant loads, for example, it represents this at an aggregate level, not with respect to any specific site.

A further, key issue in environmental assessment is definition of the baseline or comparator. This requires definition of the analytic system boundary and purpose. Neither are trivial issues and both entail a degree of normative judgement. System boundary issues are discussed below. The issue of baseline or comparator is particularly important in a biofuels context, where major land use changes are occurring or have occurred, and where the acceptability of these is viewed very differently by different stakeholders; where the definition of non-biofuel alternatives for comparison (fossil, nuclear, other renewables) is complicated by the need for a wide range of policy, economic, social and technological assumptions (which are usually organised in a scenario framework); and where the issue of scale is particularly important, in that what may be justifiable on a small scale may not be so at a large scale. Finally, the definition of what is sustainable is also partly normative. In short, all these issues and others frame the context in which environmental and ecological impacts are considered: measurement of such impacts is only the beginning of an environmental assessment of ethanol as a biofuel.

27.5.1 Site impacts

These are feedstock specific, but beyond this, in general the degree of environmental impact is related to the preceding land use and the degree to which best management practices are used in the agricultural system and conversion processes employed.

Further detail is provided on a per-ethanol-feedstock basis in other chapters, particularly that on sugarcane. The impacts of ethanol production summarised by Oliveira et al [294] are largely covered in those chapters, with the exception of the following. Pimentel and Pimentel (1996, in ibid) point out that corn causes serious soil erosion in the United States, amounting to values of approximately 22.2 Mg per ha, which is 18 times faster than the rate of soil formation. Pimentel [190] also reports that in some western irrigated corn acreage, groundwater is being mined at a rate 25% faster than the natural recharge of its aquifer [294]. Although the use of ethanol reduces emissions of carbon monoxide, there is some evidence that its use may lead to increased ambient levels of other air pollutants, specifically aldehydes and peroxyacetyl nitrates, which are toxic and possibly carcinogenic in animals [294]. Hodge [299] states that the use of ethanol as an oxygenate in reformulated gasoline in the United States contributed to the increase of ozone through higher levels of volatile organic compounds and NOx emissions.

Niven [300] provides a comprehensive review of the air, water and soil quality impacts of ethanol in different blends. Regarding air quality, he concludes that it
appears that E10 (10% ethanol, 90% gasoline) may offer some advantages over E0 (unleaded gasoline) in reducing particulate and CO emissions, and (with Reid Vapour Pressure control\textsuperscript{10}) in reducing total hydrocarbon and air toxic (especially benzene) emissions. However, without RVP control (and possibly even with it), the total hydrocarbon and air toxic emissions of E10 may be higher than those of E0 due to evaporative losses. In addition, the life cycle emissions of hydrocarbons, CO and particulates may negate the vehicle emission benefits. Even with RVP control, E10 is known to cause substantially higher acetaldehyde and ethanol emissions, and higher NOx emissions and permeation losses, all contributing to the higher ozone potential of E10 [300].

Regarding soil and water quality, Niven (ibid: pg 544) concludes that E10 increases both the risk and the severity of soil and groundwater contamination. For example, in California, the state-wide adoption of E10 is predicted to double the number of drinking water wells affected by benzene [301]. The enhanced risk of E10 relative to E0 is not associated with ethanol itself, but is caused by its impact on other petroleum fuel constituents, and on the behaviour of the fuel as a non-aqueous phase liquid. For example, ethanol reduces the interfacial tension of gasoline with respect to water, enabling the ethanol-gasoline non-aqueous phase liquid (i.e. in undiluted form) to enter smaller pore spaces, and to infiltrate more easily through the vadose zone (subsoil) down to the water table. Leaks can only be minimized, not prevented, and contamination can remain in place for decades or centuries. Niven (ibid) infers that this should obviate the use of E10 as a fuel, except where groundwater impacts are not (nor likely to be) of concern. He states that the subsurface impacts of E85 are as yet unknown (ibid: 547).

\textbf{27.5.2 LCA system boundary issues}

When calculating energy and GHG balances, it cannot be over-emphasised that the LCA system boundary is critical. For example, Giampietro et al (1997, in [294]) estimate that the energy required to clean up BOD from distillery wastes (e.g. the liquid vinasse that is applied to Brazilian soils at high volumes per ha) is 10.5 GJ per m$^3$ of ethanol produced. Considering this additional requirement, ethanol energy balances would be reduced by 61% and 31% for sugarcane ethanol and corn ethanol, respectively. Avoiding the raised BOD would not affect CO$_2$ balances for Brazilian ethanol, as about 90% of electrical energy in the country is provided by hydroelectric plants. However, in the United States, owing to the large-scale use of fossil fuels for energy generation, Oliveira et al [294] estimate that avoiding the BOD increase would increase CO$_2$ emissions by 112%. In short, LCA headline results on energy and GHG balances for ethanol production have a strong potential to unwittingly mislead.

\textsuperscript{10} US EPA (2007) states: “Reid Vapor Pressure, or RVP, is a measure of a gasoline's volatility at a certain temperature and is a measurement of the rate at which gasoline evaporates and emits VOCs; the lower the RVP, the lower the rate of evaporation. The RVP of gasoline can be lowered by reducing the amount of its more volatile components, such as butane. Lowering RVP in the summer months can offset the effect of high summer temperatures upon the volatility of gasoline, which, in turn, lowers emissions of VOC. Because VOC is a necessary component in the production of ground level ozone in hot summer months, reduction of RVP will help areas achieve the NAAQS for ozone and thereby produce benefits for human health and the environment.”
27.5.3 GHG displacement
Doornbosch and Steenblik [248] refer to IEA [249, 252] and Farrell et al [253] in estimating the GHG benefits of sugarcane and other current ethanol sources. The best performance of the current ethanol options is achieved by ethanol from sugarcane in Brazil, with the potential to reduce total life-cycle GHG emissions by up to 90% relative to gasoline. Ethanol from cellulosic feedstocks is next best, with typical estimates placing their reduction in the range of 70 to 90% [252]. In some cases, the savings could approach and even exceed 100% with, for example, the cogeneration of electricity that displaces coal-fired electricity from the grid (though so far these estimates mainly come from engineering studies and only a few large scale production facilities). Next in terms of GHG efficiency are ethanol from sugar beet and biodiesel from Malaysian palm oil and EU rapeseed respectively, with GHG reductions of roughly 40% to 50%. Finally, ethanol from starchy grains yields the smallest GHG reduction. Re the latter, Farrell et al. [253] compare several reports published on maize (corn) ethanol production in the US and conclude that the “best point estimate” would be a reduction of GHG emissions of only 13% because fossil fuels are used as a fuel in the production process and the energy inputs are almost 80% of the energy output. Even then, one has to assign a “credit” to the major co-product of grain-based ethanol: dried distillers grains with solubles (DDGS) [248].

27.5.4 LCA performance
The Swiss Institute, EMPA ([33 in [248]]) performed a full life cycle assessment of some 26 biofuel types, though some were identical but of different nationality, comparing these to LCA of transport fuels derived from petroleum and natural gas. Indicators included damage to human health, ecosystems and the depletion of natural resources, all aggregated in a single indicator (UBP). Most biofuels were found to have an overall environmental performance worse than gasoline, though with a widely differing relative performance. Maize-based ethanol in the USA earned a particularly poor environmental score, and ethanol from sugar beet and sugarcane scored only moderately better than gasoline in terms of their overall environmental impacts. Biodiesel scores were also generally negative. Only when waste products such as recycled cooking oils are used do their overall environmental performances fare better than that of gasoline. Biofuels made from woody biomass were rated better than gasoline in all cases.

27.5.5 Scale limits (land take)
Oliveira et al [294] memorably illustrate the limits of ethanol produced via corn (maize) fermentation. Assuming 2005 ethanol production conditions and an annual increase of 4% in the US automobile fleet, they determined that by 2012, all the available cropland area of the United States would be required for corn production if the whole automobile fleet were to use E85. By 2036, not only the entire US cropland area but also the entire land area now used for range and pasture would be required. Finally, by 2048, virtually the whole country, with the exception of cities, would need to be covered by corn.
27.6 Social context

This is feedstock-specific. As a vehicle fuel, ethanol has some social advantages in that it requires little in the way of behaviour change and fits easily into existing socio-technical systems relating to transport. Large scale production of ethanol for domestic vehicle fleets is typically supported by specific national policies. Thus Oliveira [294] lists factors that in the mid-1970s led Brazil to adopt a large-scale ethanol program: heavy Brazilian dependence on fossil fuels at that time; the military government’s concerns about national sovereignty; decreases in oil production by the Organization of the Petroleum Exporting Countries; and a low sugar price, with the consequent possibility of bankruptcy for sugar industrialists. The Brazilian government established a program of subsides and protection from alcohol imports [294].

Niven [300] reminds us of a wholly different public perceptions issue when he refers to a widespread public controversy in Australia over the sale of ethanol-enriched unleaded petrol. It is salutary to learn that this had little to do with environmental impacts. During 2002, press reports revealed that gasoline was being sold in Australia at levels in excess of 10% ethanol by volume, and in some cases higher than 20%, without any labelling to indicate this (ibid). Following a protracted public debate, which mainly focused on the potential damage to car engines and components, the Australian Government announced that it would limit the ethanol content of gasoline to 10%, despite evidence that possibly a third of Australia’s cars would not operate satisfactorily on a 10% ethanol blend [302]. Niven reports (ibid) that subsequent to this decision, the major oil producers in Australia have largely avoided retailing ethanol enriched gasoline, due to the poor public relations image of ethanol-enriched blends.

Niven (ibid: 546) also points to the highly subsidised nature of ethanol production and to the concentrated nature of the industry. Whether one considers these to be problematic is a matter of opinion, but is notable nonetheless. Many forms of renewable energy receive subsidies, though whether ethanol produced via substantial petrochemical inputs can be deemed renewable is debateable. Nevertheless, for example, US Federal ethanol subsidies—not counting state or broader agricultural subsidies—were in the late 1990s US$810 million p.a. [303]. Also in the late 1990s, Brazil’s fuel consumers paid more than US$2 billion/year extra for overpriced gasoline to subsidize ethanol production [304]; several years later, a separate study estimated US$100 million/year was transferred to sugarcane farmers as hidden subsidies [305].

As stated, Niven (ibid: 546) observes that the Australian and US ethanol industries are highly concentrated. In the US, the largest firm is claimed to have a 41% market share, whilst the top four firms have a 58% share [299]. Including production capacity and marketing agreements, four companies are claimed to control 95% of supply [299]. Australia has two ethanol producers, Manildra Pty Ltd and CSR Ltd, of whom Manildra provides 87% of supply [306]. Both US and Australian manufacturers are protected from import competition. Niven (ibid) argues that such oligarchical (or monopolistic) industries and restrictions on free trade can only encourage inefficiency and stifle innovation, to the detriment of consumers and long-term societal interests.
27.7 Applications
In this context, the principal application of ethanol is as a vehicle transport fuel (i.e. for use in internal combustion engines). Uptake has been facilitated by the development of flex-fuel vehicles that can run on any ratio of gasoline (petrol) / ethanol blend, up to 85% ethanol. For example, in 2005, Brazil’s carmakers sold more vehicles adapted to run on alcohol than conventional petrol-driven models, with flex-fuel cars taking 53.6% of the Brazilian market [255].

27.8 Constraints
The constraints on ethanol supply to the UK are feedstock-specific. Generic issues include: the role of subsidies and trade barriers; the extent of domestic/regional use; public and policy-level precaution in relation to food-fuel competition, land use change and associated impacts, and GHG savings. The pace at which lignocellulosic technology develops is also likely to significantly affect supply.

27.9 Conclusions
Ethanol production has a strong potential to compete for food production and the biodiversity value of land. It can be produced by fermenting sugar-rich crops, by hydrolyzing starchy crops at low or high temperatures, and via lignocellulosic crops and wastes, entailing a variety of pre-treatment methods required to break down lignin.

Significant progress has been made in the past several years in all aspects of lignocellulosic conversion to ethanol and improvements have been made in microorganisms capable of converting multiple sugars into ethanol [307]. However, further cost reductions are required and will more than likely come from novel, tailored cocktails of enzymes (ibid). Until lignocellulosic methods are economically affordable, large scale ethanol production will continue to require commensurately large areas of land.

In the meantime, large scale production of ethanol via fermentation of sugarcane in Latin America is the principal option if ethanol is the chosen route for petrol substitution. This may be sustainable in some respects, if better management practices are adopted. However, in biodiversity terms the situation has already been highly destructive, and not only in Latin America. An environmental case can be made for not further expanding ethanol production from sugary and starchy crops, where this involves further biodiversity losses.
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Electricity generated by renewable sources: 1996-2005

Electricity generated (Gigawatt hours)

- Wind (1)
- Hydro
- Landfill gas
- Sewage sludge digestion
- Biogradable municipal solid waste
- Co-firing with fossil fuels
- Other (2)

1 Latest years include electricity from shoreline wave but this amounts to less than 0.05 GWh.
2 Includes the use of farm waste digestion, poultry litter combustion, meat and bone combustion, straw and energy crops, and
Appendix 1: Background to Supergen consortium, previous phase 1 activities and how they have influenced this work

In phase 1 the Supergen bioenergy consortium evaluated 25 different bioenergy systems for production of electricity, with some combined heat and power options. Work package 1 carried out techno-economic, environmental and social appraisal of these systems against a set of 52 criteria. The assessment covered entire life cycle from crop planting to end-of-life restoration and the entire bioenergy chain from production, through processing, transport, utilisation and power generation. The range of feedstocks used was relatively small, focusing on wood chip from SRC willow, miscanthus and straw. However, the range of technical systems was large, ranging from small 250 kWe gasifierCHP systems through to 25 MWe dedicated combustion plant.

Phase 2 of Supergen aims to expand this approach to consider electricity, transport and heat applications. This requires a much wider range of feedstocks. While the energy crops of phase 1 will still be considered there is also a need to look at imported energy crops, particularly those more suited for transport fuel production. These will include purpose-grown crops such as sugar-cane and maize, but also wastes and by-products such as olive wastes and palm kernel expeller.

It is intended to carry out a thorough assessment of a number of bioenergy supply chains, representing technically diverse systems for delivering heat, electricity and transport fuels. Each system will be assessed across a range of characteristics covering the technical, economic, environmental and social aspects of bioenergy production. Therefore it is essential to start with data (collated in this report) which represents the state of the art knowledge in terms of the environmental, economic and social impacts of the feedstock production. Not all of these feedstocks will be examined in depth along full supply chains, but this report will help inform which should be chosen for full analyses as well as providing the main data for the subsequent work.
Appendix 2: Consultation and evaluation process followed for choice of feedstocks

In phase 1 of Supergen the systems assessment focused on a willow SRC feedstock, augmented by miscanthus (considered to be the most commercial of the perennial grass crops) and some consideration of straw. However, the crops actually grown for Supergen 1 were reed canary grass, switchgrass and miscanthus. Waste was specifically excluded and imported feedstocks were not considered. Also the focus was entirely on electricity; therefore feedstocks more appropriate for transport fuel use were excluded by default.

In Supergen Biomass and Bioenergy 2, it is necessary to ensure that a good cross-section of relevant feedstocks are chosen for analysis, that build upon the work done in Supergen 1 and that also fit appropriately with the ongoing activities in other themes in Supergen 2. It is also important that the resource evaluation covers a comprehensive range of feedstocks, even if these are not all followed through with full systems analyses.

Considering feedstocks for evaluation

Section 1.2 sets out the process followed for the identification of feedstocks for assessment. The question of which feedstocks to evaluate was raised at the theme 6 kick-off meeting. The following responses were obtained from the participants:

- SRC
- Forestry residues
- Grasses
- Waste
- Ethanol
- Soy
- Jatropha
- Palm-nut waste
- Marine biomass

The industrial partners not present at that meeting were then additionally canvassed on which feedstocks they would like to see included and the following were identified:

- Miscanthus – especially for a small-scale electrical application
- Reclaimed or recovered biomass

It is important that theme 6 builds upon the work being done in other parts of Supergen. Most relevant to this is the theme on resource assessment within Supergen phase 2. Characterisation tasks within that theme are focusing on willow, miscanthus, high forest residues and cereal residues. Work on yield and biotechnology is focusing on willow and miscanthus. Work on energy crop agronomy in phase 1 focused on grasses and will focus on willow in phase 2. Work on biomass supply chains will focus on SRC and grasses.

Work on theme 2 focuses on characterisation of the biomass resource and will include work on forestry co-products and cereal straws. There is also a specific task in theme 2 focused on material arising from the biological mechanical treatment of industrial
and municipal wastes. Different methods of producing pellets from SRC willow are also being investigated.

Work in theme 3 focuses on thermal conversion, including detailed modelling of the systems. The outputs from this theme tend not to feed directly into theme 6 work, but are relevant in that they define the sphere of activity for our partners, who are experts in the thermal conversion technologies. The general aim of this theme is to extend their work from energy crops to co-products and some residue and waste materials. There is also a specific task focused on utilisation of bio-refinery wastes and residues. Work on fast pyrolysis in task 3F is to focus on pyrolysis of bark, rape straw and rape meal. Theme 4 is to include a consideration of solid recovered waste fuels. Theme 5 focuses on production of transport fuels and task 5B starts with a consideration of likely feedstocks for the UK.

Table 1.1 lists the suggested feedstocks referred to above and broadly evaluates their relevance for Supergen phase 2 work. Each feedstock is assessed based on four criteria: its relevance to industry; how complementary it is to other Supergen 2 activities; whether it is additional to work already done in Supergen 1 and whether or not there is sufficient data and/or experience within the consortium to attempt a sensible systems assessment. Correlation with these criteria has been scored as high (H), medium (M) or low (L). The feedstocks have then been ranked with 2 points for each high score, 1 point for medium and none for low to obtain an overall score in the right hand column.
Table 1.1 Feedstocks suggested for consideration in Supergen phase 2 work

<table>
<thead>
<tr>
<th>Feedstock</th>
<th>Relevance to industry</th>
<th>Complementary to other Supergen activities</th>
<th>Additional to activities in Supergen 1</th>
<th>Availability of data/experience of partners</th>
<th>Ranking</th>
</tr>
</thead>
<tbody>
<tr>
<td>SRC</td>
<td>H</td>
<td>H</td>
<td>L</td>
<td>H</td>
<td>6</td>
</tr>
<tr>
<td>Forestry residues</td>
<td>M</td>
<td>H</td>
<td>H</td>
<td>H</td>
<td>7</td>
</tr>
<tr>
<td>Grasses</td>
<td>H</td>
<td>H</td>
<td>M</td>
<td>H</td>
<td>7</td>
</tr>
<tr>
<td>Reclaimed wood</td>
<td>H</td>
<td>L</td>
<td>H</td>
<td>M</td>
<td>5</td>
</tr>
<tr>
<td>Waste stream from MBT</td>
<td>H</td>
<td>H</td>
<td>H</td>
<td>H</td>
<td>8</td>
</tr>
<tr>
<td>Bio-refinery wastes</td>
<td>M</td>
<td>H</td>
<td>H</td>
<td>H</td>
<td>7</td>
</tr>
<tr>
<td>Ethanol</td>
<td>H</td>
<td>H</td>
<td>H</td>
<td>M</td>
<td>7</td>
</tr>
<tr>
<td>Wood pellets</td>
<td>H</td>
<td>H</td>
<td>H</td>
<td>H</td>
<td>8</td>
</tr>
<tr>
<td>Soy</td>
<td>M</td>
<td>M</td>
<td>H</td>
<td>L</td>
<td>4</td>
</tr>
<tr>
<td>Jatropha</td>
<td>H</td>
<td>M</td>
<td>H</td>
<td>M</td>
<td>6</td>
</tr>
<tr>
<td>Palm-nut waste</td>
<td>H</td>
<td>M</td>
<td>H</td>
<td>M</td>
<td>6</td>
</tr>
<tr>
<td>Marine biomass</td>
<td>M</td>
<td>H</td>
<td>H</td>
<td>H</td>
<td>7</td>
</tr>
</tbody>
</table>
A key aim of theme 6 is to compare different potential uses for each biomass stream, so it is also important to ensure that our choice of feedstocks is sufficiently diverse to include recognised feedstocks for each sector: electricity, transport and heat. Table 1 categorizes the applicability of each of these feedstocks for each of the 3 sectors. The transport fuels sector has been divided into 3 subsectors: biodiesel, bioethanol and second generation fuels, since the feedstocks appropriate for each of these conversion technologies can be quite different. It should be noted that there are no plans to carry out any substantial work into biodiesel or bioethanol production within phase 2 of the Supergen consortium. However, biodiesel is currently being produced in the large quantities within the UK and bioethanol is commercial on a world-wide basis; so these effectively represent the current baseline for biomass-based transport fuels. It would, therefore, be appropriate to include within theme 6 a brief consideration of biodiesel and bioethanol production. These would rely heavily on analyses already performed by others, but would include an assessment of the impact of potential improvements in production alongside an evaluation of alternative technologies. It is important therefore to ensure that feedstocks appropriate for this are included in the mix chosen.

For the purposes of ensuring that a sufficiently wide range of feedstocks have been chosen to allow comparisons across the relevant energy sectors, it has been assumed in table 2 that oil crops (such as soya, rape and palm) would be used to produce oils that would be converted to biodiesel (first generation biofuels). It is, of course, true that these crops could be utilised for heat or electricity production via combustion. However, generally they are considered to be more appropriate for use in the transport fuel sector and so the focus will be on their use for transport fuel. It would be interesting to carry out a cross-comparison of a fuel that is normally considered for transport use and see how it performs when utilised for power generation instead or vice versa. However, this would be a peripheral activity if time permits within the research programme.

Resources containing significant starch or sugar would be fermented to produce bioethanol. This is also a first generation biofuel, but is quite distinct from biodiesel and worthy of separate appraisal. As stated above, this is not being studied in depth by any of the Supergen partners, other than as part of the biorefinery concept. However, it is an established technology and is of interest to some of the industrial partners. Therefore it is appropriate to assume that we should consider within our resource assessment materials which could be used to produce bioethanol via fermentation. Additionally direct importation of bio-ethanol from Brazil or other South American countries should be considered.

Bioethanol can also be produced via a second generation technology, using lingo-cellulose from whole crops. This could be done via hydrolysis and fermentation, gasification and synthesis or pyrolysis. All these techniques are still under development, to varying extents. For purposes of the resource assessment the details and status of the technology are not important. It is simply important to note that a variety of lingo-cellulosic material can be utilised to produce biofuels using second generation technologies. Some evaluation of this should be included in Supergen 2, although it is likely to be limited by the extent of process evaluation going on in this area in other themes.
Table 1.2 broadly depicts the applicability of the feedstocks already identified in table 1 for the demand sectors. Although the technology options to be considered in the Supergen 2 programme will be defined separately it is important to ensure that the resource assessment includes a range of material that is potentially applicable to the different technologies. Where the feedstock would generally be considered suitable for the conversion technology the cell is darkly shaded in red. Where the feedstock could theoretically be used for that purpose but this would not generally be considered the cell is lightly shaded in pink. The feedstocks have been reordered in accordance with ranking obtained in table 1.

### Table 1.2 Potential feedstocks organised by potential application

<table>
<thead>
<tr>
<th>Feedstock</th>
<th>Electricity</th>
<th>Heat</th>
<th>Transport fuels</th>
<th>Biodiesel production</th>
<th>Ethanol production</th>
<th>Second generation technologies</th>
</tr>
</thead>
<tbody>
<tr>
<td>Waste stream from MBT</td>
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<tr>
<td>Wood pellets</td>
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<td>Forestry residues</td>
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<tr>
<td>Grasses</td>
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<td></td>
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<tr>
<td>Bio-refinery wastes</td>
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<tr>
<td>Ethanol</td>
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<td>Marine biomass</td>
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<td>SRC</td>
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<tr>
<td>Palm-nut waste</td>
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<tr>
<td>Jatropha</td>
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<tr>
<td>Reclaimed wood</td>
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<tr>
<td>Soya</td>
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</tbody>
</table>

Table 1.2 shows that few of the feedstocks in the list initially identified that are suitable for analyses of first generation technologies for biodiesel production or bioethanol production. These needed to be added. As none of these feedstocks have been specifically identified by partners for inclusion it makes sense to include two of the more common feedstocks for these technologies. There is already biodiesel production capacity within the UK relying on recovered vegetable oil. It makes sense
therefore to include this in the resource assessment. In addition it would be interesting to compare this to a feedstock of agricultural origin and rape would be ideal for this, as it is an established crop in the UK already used for this purpose. For bioethanol production the key is to have a feedstock with high sugar or starch content which is fermentable. In countries such as Brazil sugar cane is the main feedstock driving the industry, but the UK climate and agricultural practices is more conducive to production of starchy feedstocks, such as wheat or barley. It is also possible to produce bioethanol from cellulose feedstocks, although this requires additional steps in the production process to release the sugars, which are less commercially proven. These feedstocks are, in any case, already included in the resource assessment.

Therefore three additional feedstocks should be considered in the resource assessment: recovered vegetable oil, rape and wheat.

It is also important to ensure that the feedstocks that have already been identified by stakeholders, including NGOs as of particular importance or concern, are included. A review of prominent internet-based concerns relating to biofuels, undertaken in January 07 showed a wide range of issues. Recurrent concerns are:

- Adverse biodiversity impacts of clearing forest/savannah for plantations, be this for palm oil, soy, sugar cane etc. for biodiesel etc.
- The poor carbon emissions reductions gained from fermenting intensively farmed agricultural crops (notably corn and wheat) to bioethanol.
- Nitrogenous gaseous emissions from agricultural inputs
- Concern over long distance transport emissions for imported biomass and hence reduced climate change benefits
- Adverse biodiversity effects of set-aside land being converted to energy crops
- The environmental costs of biofuels exceeding the benefits due to very high land take being required for substantial fossil fuel replacement
- Food-fuel competition and associated food price increase, water shortage etc
- Mistrust of genetically-engineered crops and cross-pollination with non-GM plants.

Regarding feedstocks for heat and power, of recurrent public concern are:

- Nuisance and odour from MSW-type waste
- Gaseous emissions from both ‘contaminated’ and ‘clean’ feedstocks
- Mistrust of the regulatory processes relating to waste emissions
- Vehicle nuisance and emissions (inc GHG balance) from feedstock transport
- UK landscape changes, biodiversity loss, high land take.

Many of these issues are not feedstock-specific; however, to adequately address them, it is necessary to choose feedstocks that cover the range of issues identified. Extracting these from the information above it would be useful to include palm oil, soya or sugar cane to assess concerns regarding loss of existing plantations. Soya has already been included in the table above. Wheat and corn/maize should be included to analyse carbon benefits of fermentation to bioethanol. Wheat has already been included but neither corn nor maize have been. Again it would be useful to establish if the issues related to corn and maize are similar, to establish if additional feedstocks need to be added. Some long distance imports should be included and this is already the case with the feedstocks included above. However, discussions with others more closely involved with imported material suggested that a selection of other
international feedstocks should be included, including cynara cardunculus, sweet sorghrum and olive residues. Some energy crops should be included and these have already been included in the list above.

Sugar beet can be grown in the UK and used to provide a basis for ethanol production. This is particularly relevant where co-production alongside a sugar factory takes place. There is one facility of this type already operational in the UK. However, input from the industrial mentors on this task indicated that it is unlikely that there would be significant further expansion of this resource or technique and therefore it has not been covered in this review.

Market trends for biofuel production to date have shown that biodiesel production tends to dominate in Europe with bioethanol dominating in the Americas. The base for bioethanol production is more firmly established than that for biodiesel. It is therefore more likely that the UK would import significant quantities of bioethanol from overseas than that it would import biodiesel. It is important when considering future bioenergy scenarios that the origin and impact of all resources are considered; whether they are raw or finished products. It is considered likely that UK bioenergy will comprise a proportion of imported bioethanol in the future produced overseas from relevant feedstocks. Therefore special consideration has been given to bioethanol in this report; even though it is not strictly a “resource”. This allows for accounting of the impact of all bioenergy and also will allow a comparison of indigenous and overseas production of energy carriers fulfilling the same utilisation function.