CARBON AND ENERGY MODELLING OF BIOMASS SYSTEMS: CONVERSION PLANT AND DATA UPDATES

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EXECUTIVE SUMMARY

1. This is the Final Report on work conducted by the Resources Research Unit of Sheffield Hallam University for ETSU, AEAT Environment under Agreement No. B/U1/00644/00/00. This work contributes to the evaluation of carbon and energy budgets of the production and use of biomass as a fuel. In particular, the work consisted of updating the energy and carbon requirements of important materials used in the production, transport and storage of biomass fuels, and the energy and carbon analysis of the construction and operation of biomass energy conversion technologies in use and under development in the United Kingdom.

2. The terminology, definitions and conventions commonly adopted in the calculation of total energy consumption and associated carbon dioxide emissions are introduced. Specifically, the concepts of primary energy, as the amount of energy available in resources in their natural state, and associated carbon dioxide emissions, from the combustion of fossil fuels and other important sources, are established. Additionally, the terms energy requirement and carbon requirement, as the amount of energy consumed and associated carbon dioxide released during provision of a physical unit of a product or service, respectively, are specified. Methods of energy and carbon analysis, consisting of process analysis and statistical analysis based on actual physical and cost data, respectively, are explained and methods of presenting results, which rely on a standard, transparent format, are described.

3. Important contributions to the total primary energy inputs and associated carbon dioxide outputs of biomass conversion technologies are identified using wood-fired electricity generation as an example. Updated results, in the form of energy and carbon requirements, are presented for diesel fuel, ammonium nitrate fertiliser, rock phosphate fertiliser, single superphosphate fertiliser, triple superphosphate fertiliser, potash fertiliser, lime, fencing, storage facilities, cement, concrete and constructional steel are presented. Results for biomass conversion plant components are also provided from the statistical analysis of United Kingdom input-output tables.

4. The primary energy inputs and associated carbon dioxide outputs are derived for the manufacture and construction of a selection of biomass conversion technologies, including demonstration-scale wood gasification power only plants, a large-scale wood gasification power only plant, a modular wood gasification combined heat and power plant, a large-scale wood pyrolysis power only plant, a small-scale wood burning heat only plant, a large-scale wood burning heat only plant and a large-scale rape methyl ester liquid biofuel plant. These definitive results are obtained from analyses based on actual and simulated weight breakdowns for specific examples of such biomass conversion technologies. Results are compared and power rule trends with plant scale are illustrated. Comparison shows that there are significant differences between results due to the effects of both technology and scale. The particular importance of current study as a source of definitive results for the manufacture and construction of biomass conversion technologies is emphasised. Finally, contributions to primary energy inputs and associated carbon dioxide outputs from start-up fuel, plant maintenance and decommissioning are discussed.

5. Appendices provide complete explanations of the mathematical basis of methods of presenting results, the evaluation of prominent inputs to biomass systems, energy and carbon requirements from process and statistical data sources, and a review of existing studies of energy and carbon analysis of biomass conversion technologies and related systems.

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1. INTRODUCTION

1.1 Context

This is the Final Report on work conducted by the Resources Research Unit of Sheffield Hallam University for the Energy Technology Support Unit (ETSU) of AEA Technology Environment under Agreement No. B/U1/00644/00/00. It provides results which contribute to the evaluation of carbon and energy budgets of the production and use of biomass as a fuel. Specifically, this work consists of "Updating Energy and Carbon Requirements of Important Materials Used in the Production, Transport and Storage of Biomass Fuels" and "Analyses of Energy and Carbon Requirements from Construction and Operation of Conversion Technologies in Use and Under Development in the United Kingdom". This work fits within the context of a range of studies which have examined the **energy** and/or **carbon budgets** of biomass fuels. In most instances, these studies have calculated the energy consumed and/or the carbon dioxide (CO_2) emissions associated with growing, harvesting and utilising a variety of sources of biomass as fuels for heating, electricity generation, etc. Such work has been undertaken for a number of different reasons. However, the most prominent and relevant considerations have usually been related to the evaluation of prospective savings in conventional energy resources and the assessment of potential reductions in CO_2 emissions. Amongst the work conducted for ETSU have been studies of the energy and carbon budgets for short rotation coppice (SRC) and forestry wastes (Refs. 1 and 2), straw (Ref. 3) and miscanthus (Ref. 4). The calculations in these studies relied on diverse sources for the energy and carbon data, referred to here as **energy** and **carbon requirements**, respectively. However, most of these data sources are relatively dated and there is a recognised need to update energy and carbon requirements in order to accommodate fundamental changes in energy production and consumption over time. Additionally, there has been a general lack of detailed and reliable information for estimating the total energy inputs and CO_2 outputs associated with constructing, operating, maintaining and decommissioning biomass conversion technologies. Both of these important issues have been addressed by this current work.

1.2 Aims and Objectives

The results of this work is intended to provide general support for the energy and carbon modelling of biomass production and utilisation systems. Consequently, the principal aims of the current work are:

- to provide updated results for modelling the energy and carbon budgets for biomass production and utilisation and,

- to derive estimates of the total energy consumption and CO_2 emissions associated with the construction, operation, maintenance and decommissioning of a selection of biomass conversion technologies.

It was proposed that these aims would be achieved by means of the following major objectives:

- Confirmation of prominent inputs associated with the energy and carbon modelling of biomass production and utilisation systems, in the form of SRC and forestry wastes used to provide wood chips for electricity generation.

- Selection of biomass conversion technologies for further investigation.

- Review of existing research on the energy and carbon budgets of biomass conversion technologies.

- Updating of energy and carbon requirements for diesel fuel.

- Updating of diesel fuel consumption data for agricultural machinery and road freight vehicles.

- Updating of energy and carbon requirements for prominent inputs, initially regarded as harvesting and chipping machinery and fertilisers for biomass production systems, consisting of SRC and forestry wastes, and bulk construction materials for biomass conversion technologies, using process data sources.

- Updating of energy and carbon requirements for infrastructure and storage components in biomass production systems, consisting of SRC and forestry wastes, using process data sources.

- Updating of energy and carbon requirements for biomass production systems, consisting of SRC and forestry wastes, and biomass conversion technologies using statistical data sources.

- Derivation of reference cost breakdowns and weight inventories for selected biomass conversion technologies.

- Determination of energy inputs and associated CO_2 outputs from the operation (mainly start-up fuel), maintenance and decommissioning of selected biomass conversion technologies.

- Development of a spreadsheet, based on Excel software, for recording and using energy and carbon requirements for bulk materials and components, and cost breakdowns and weight inventories for selected biomass conversion technologies.

1.3 Programme of Work

The programme of work to accomplish these aims and objectives extends began in January 2000 and was originally intended to be completed by December 2000. Due mainly to delays encountered with the availability of data, the timescale for the work was extended to February 2001. An initial Contract Meeting was held at ETSU on 19 January 2000 to discuss project planning and to draw up a provisional list of biomass conversion technologies for subsequent investigation. A subsequent Contract Meeting took place at ETSU on 17 January 2001 to review progress and to plan completion of the work. The agreed programme of work consists of the following activities:

Activity 1. Project Planning:

Activity 2. Carbon and Energy Requirements of Diesel Fuel:

Activity 3. Process Carbon and Energy Analysis:

Activity 4. Biomass Fuel Production and Storage Inventory Analysis:

Activity 5. Statistical Carbon and Energy Analysis:

Activity 6. Cost Breakdowns and Weight Inventories for Biomass Conversion Technologies:

Activity 7. Spreadsheet Development:

Activity 8. Reporting:

An Interim Report, covering progress between January 2000 and March 2000, was produced in March 2000 and revised in June 2000 (Ref. 5). The particular issues addressed by the Interim Report were; the identification of the most prominent inputs to biomass systems, in terms of the largest contributions to total energy consumption and associated CO_2 emissions to the generation of electricity from wood chip derived from SRC and forestry wastes; a review of existing studies of the energy and carbon budgets of biomass systems; the formulation of a standard method for presenting the results of energy and carbon modelling; and preliminary results for the energy and carbon requirements of diesel fuel, fertilisers and bulk materials. The work presented in the Interim Report provides the basis for the specific areas covered by the current Final Report.

1.4 Report Structure

The remainder of the Final Report is divided into two major parts; Section 2 which presents updated energy and carbon requirements for prominent inputs to biomass systems, and Section 3 which provides the estimated energy inputs and associated CO_2 outputs for the construction, operation, maintenance and decommissioning of selected biomass conversion technologies. Within Section 2, basic terminology, definitions and conventions are described in Section 2.1, methods of energy and carbon analysis are explained in Section 2.2, methods of presenting results are set out in Section 2.3, and the basis for the current results is established in Section 2.4, with specific results given for diesel fuel, fertilisers, fencing, storage facilities, cement and concrete, constructional steel and biomass conversion plant components in Sections 2.4.1 to 2.4.7, respectively. In Section 3, results for biomass conversion technologies are considered. The general procedures adopted are summarised in Section 3.1 and the methods for calculating the results for construction are outlined in Section 3.2. Results are presented from the energy and carbon analysis for the construction of a demonstration scale wood gasification power only plant, a large scale wood gasification power only plant, a modular wood gasification combined heat and power plant, a large-scale biomass pyrolysis power only plant, a small-scale wood burning heat only plant, a large-scale wood burning heat only plant, and a large-scale rape methyl ester liquid biofuel plant in Sections 3.2.1 to 3.2.7, respectively. A comparison of results is presented in Section 3.2.8. The issues of start-up fuel, maintenance and decommissioning are discussed in Sections 3.3 to 3.5. Supporting information on methods of presenting results is given in Appendix A, prominent inputs to biomass systems are identified in Appendix B, detailed summaries of the energy and carbon requirements prominent inputs derived from process data sources are presented in Appendix C, the energy and carbon requirements for biomass conversion plant components derived from statistical data sources are summarised in Appendix D, and a review of existing studies on energy and carbon budgets for biomass systems is provided in Appendix E.

2. ENERGY AND CARBON REQUIREMENTS

2.1 Terminology, Definitions and Conventions

In order to provide a sound basis for understanding the results presented here, it is necessary to introduce essential terminology, with definitions and related conventions which are commonly used in the calculation of total energy consumption and associated CO_2 emissions. Most of the energy terminology derives from the formal establishment of the principles of **energy analysis** during the 1970's (Refs. 6 and 5). In particular, three specific forms of energy were recognised; primary energy, delivered energy and useful energy. **Primary energy** consists of the amount of energy available in resources in their natural state, such as coal, natural gas, oil and uranium deposits in the ground. Following their extraction and processing, these natural energy resources are converted into suitable forms of fuels and electricity which can be used by consumers. These forms of energy are known collectively as **delivered energy**. Consumers use fuels and electricity in appliances, equipment, etc., to provide heat, light, motive power, etc. Such energy is referred to collectively as **useful energy**.

In terms of measurement, there are important differences between these forms of energy. These differences are due to the inefficiencies of the processes used for converting primary energy to delivered energy and from delivered energy to useful energy. Additionally, the results measured in primary, delivered or useful energy terms provide answers to different questions. Primary energy indicates natural resource depletion, delivered energy is associated with the purchasing decisions of consumers and useful energy relates to the energy services which end users require. As an indicator of natural resource depletion, primary energy should refer to non-renewable energy resources only. Hence, subsequent calculations would include the energy of all fossil and nuclear fuels whilst excluding solar, hydro, tidal, wave and wind power, and biomass and geothermal energy.

At least three types of energy input can be taken into account in energy analysis calculations; direct energy inputs, indirect energy inputs and feedstocks. **Direct energy inputs** equal the energy which is released when fuels are burnt and electricity is consumed in appliances, equipment, etc., used in any activity which provides a product or service. **Indirect energy inputs** arise from the consumption of energy in other processes or operations which produce the raw materials, chemicals, machinery, etc., used by the activity under consideration. Such indirect energy inputs are sometimes referred to as embodied energy. Indirect energy is associated with fuels and electricity as well as all the other inputs to an activity. This occurs due to the need to use energy in the production of such fuels and electricity. The final type of energy input consists of **feedstocks** which are potential sources of energy that are used as sources of raw materials. An example of this would be crude oil used to produced organic chemicals and plastics. The energy content of the feedstock is counted as an energy input since its use still results in the depletion of a non-renewable energy resource. The **total energy input** to any activity is equal to the sum of all direct energy inputs, indirect energy inputs and feedstocks. By convention, Systeme Internationale units have been recommended for use throughout energy analysis. Hence, energy inputs of all types are measured in joules (J), or multiples thereof, especially megajoules (MJ = 10^6 joules).

For convenience, there is a terminology for the results derived by means of energy analysis. If the product or service under investigation is specified in physical terms, such as weight, then the result of subsequent energy analysis is referred to as the **energy requirement** which is measured, for example, in megajoules per kilogram (MJ/kg). Alternatively, the output of an activity could be described by its financial value, such as in £ sterling, in which case energy analysis would provide a result known as the **energy intensity** measured, for example, in megajoules per £ sterling (MJ/£). The use of energy requirements and energy intensities in energy analysis studies usually involves combining them, as multipliers, with physical data, such as weight breakdowns, or financial data, such as cost breakdowns, respectively. However, the way in which this is accomplished requires careful application so that these multipliers are used consistently and correctly. Particular care must be exercised when using energy intensities as multipliers since significant differences can arise in the meaning of financial values. For example, the financial value of a product sold to the final consumer by a retailer is generally higher than its financial value as a product supplied by the factory to the retailer. Hence, strict specification and consistent application of such multipliers is essential in order to derive reliable and relevant results from energy analysis studies.

Additional specification is needed for multipliers associated with fuels and electricity by attaching the terms gross or net to the energy requirement. The **gross energy requirement** of a fuel or electricity consists of the total primary energy required, from all sources, both directly and indirectly, to produce one unit of output, in either energy or other physical terms. Occasionally, the inverse of the gross energy requirement is quoted and referred to as the **primary energy efficiency**. It will be noted that the gross energy requirement of a fuel or electricity incorporates the energy content of that fuel or electricity. In contrast, the **net energy requirement** excludes the energy content of the fuel or electricity. Gross and net energy requirements are used for different purposes in energy analysis. In particular, energy analysis studies which are evaluating natural energy resource depletion are based on calculations involving gross energy requirements for fuels and electricity.

The terminology and definitions used in the evaluation of CO_2 emissions are less well-established. Indeed, even the terms which have been coined to describe such evaluation are diverse and not standardised. These include **carbon analysis** and the preparation of **carbon budgets** and **CO_2 balances**. However, some terms have been adopted from energy analysis. For example, the **carbon requirement** is sometimes used to describe the total CO_2 emissions arising from the provision of a given product or service, measured in physical terms (such as kg CO_2/kg). Likewise, the **carbon intensity** refers to the total carbon dioxide emissions released per unit financial value of a given product or service (for example, kg CO_2/£). By similarity with energy analysis, **total CO_2 emissions** are comprised of **direct CO_2 emissions** and **indirect CO_2 emissions**. Although these are frequently produced by the combustion of fossil fuels, they can also result from other processes, such as the production of cement. For completeness, all relevant sources of CO_2 emissions must be taken into account in subsequent analysis.

When calculating CO_2 emissions from the use of fuels and electricity, suitable **carbon coefficients** or **combustion emission factors** are used. These indicate the CO_2 emissions produced per unit of energy available released when a fuel is burnt or electricity is generated (such as kg CO_2/MJ). Although such carbon coefficients include CO_2 emissions from electricity generation, they usually exclude CO_2

emissions from other fuel cycle activities, such as the construction, operation and maintenance of infrastructure for processing fuels. In order to clarify the basis of subsequent calculations, the term **gross carbon coefficient** is introduced here to represent the total CO_2 emissions produced per unit of energy available from fuels or electricity (also measured as kg CO_2/MJ). Elsewhere, this is referred to as the **total upstream and combustion emission factor** (Ref. 20).

The immediate link between energy inputs and carbon dioxide outputs through the use of fossil fuels does not apply to **feedstocks**. Depending on the particular raw material under consideration, both the energy and carbon of the original resource are effectively stored within the feedstock. As explained previously, if natural resource depletion is a key concern, then energy analysis accounts for the stored energy in the feedstock. The reason for this is that the stock of energy available from natural resources is actually reduced by this alternative use as raw materials rather than sources of energy. Furthermore, the eventual availability of this stored energy is usually linked to the release of the stored carbon, most probably in the form of CO_2 emissions. Consequently, as long as the energy is stored in the feedstock the associated carbon would be excluded from carbon analysis. There are, however, additional considerations which have to be recognised. Stored energy and carbon in materials, such as plastics, derived from fossil fuels, such as crude oil, can be released during subsequent activities, including re-use or disposal. Additionally, the carbon in fossil fuels used as feedstocks in chemical processes may be released as CO_2 emissions as a result of chemical reactions. The way in which these considerations are taken into account in carbon analysis depends on specific circumstances.

2.2 Methods of Energy and Carbon Analysis

The two main methods of calculating total energy inputs and associated CO_2 emission outputs are generally referred to as process analysis and statistical analysis. **Process analysis** involves determining energy inputs and associated CO_2 emission outputs principally using physical data for a very specific product or service. This requires considerable information on the process under examination and, ideally, all the processes in the supply chain from the original raw materials which provide all the products and services used in the process. This can be a very demanding requirement, since process analysis must be based on either exhaustive investigation of the entire supply chain and all its links and/or a very extensive database of energy and carbon requirements for all the inputs to the process under consideration. Apart from the substantial amounts of time and effort which may be needed in the collection and analysis of all necessary data, problems can also be encountered with the confidentiality or proprietary nature of the information required. The results obtained are usually very specific to a particular product or service derived from a given process at a certain time and location. This means that such results are often used with a relatively high degree of confidence since they are regarded as comparatively accurate and reliable. However, one subsequent drawback is that considerable work is usually required to obtain results which may reflect the range of sources and processes used to obtain typical products and services generally available on the economic market.

The alternative method of **statistical analysis** relies on national financial statistics which summarise all the processes and all the subsequent products and services which comprise the economy of a single country, part of a country, or collections of countries. Such statistics are normally represented by means of so-called input-output tables which can be manipulated by established mathematical procedures to derive energy and carbon intensities of groups of products and services. Provided that the input-output tables are suitably prepared and information is available on the fuel and electricity purchases of individual groups of industries, then it is possible to derive results relatively quickly and easily. Despite this particular attraction, even with highly detailed, large and disaggregated input-output tables, subsequent results consist of statistical averages for potentially-broad or general ranges of products and services. Hence, they are often regarded as relatively approximate results which are used when specific results from process analysis are not available. However, by using a variety of other statistical sources, it is possible to estimate the ranges of likely energy and carbon intensities which these results reflect. This provides indications of their comparative accuracy and reliability.

Another feature of the results of statistical analysis which may sometimes be a cause for concern is that, unlike process analysis which produces energy and carbon requirements measured per unit physical output (for example, MJ/kg or kg CO_2/kg), this method derives energy and carbon intensities measured per financial output (for example, MJ/£ or kg CO_2/kg). In addition to problems of unfamiliarity which this may create, it is necessary to use energy and carbon intensities with particular caution. The reason for this is that the financial value incorporated in an energy or carbon intensity must be equivalent to the financial value of the product or service which is being evaluated in an energy or carbon analysis. There can be substantial differences in financial values, in terms of factory-gate, wholesale or retail prices or costs. Hence, it is necessary to ensure that complementary data are used together. Because of this perceived difficulty, it is often preferred that energy and carbon intensities obtained from statistical analysis are converted to energy and carbon requirements. Again, special care is needed to achieve this properly. However, the basis for doing this here has been developed in earlier work on cost modelling for ETSU (Ref. 8). Frequently, it is necessary to combine the results of process and statistical analysis in the evaluation of energy and carbon budgets. This is mainly due to incompletely comprehensive databases. As a consequence of basic considerations which affect their derivation, results from process analysis are often used for basic products and services, whilst results from statistical analysis have to be used for more complex products and services.

2.3 Methods of Presenting Results

Many methods have been formulated for presenting the results of energy and carbon analysis in a systematic and meaningful manner. Initially, during the early stages of the development of energy analysis (Refs. 7 and 8), it was implied that single values would be used to represent the total amount of energy required to provide any given product or service. However, it quickly became apparent that single values lacked the detail to present all the information and assumption which may be incorporated in a result. For example, it became necessary to distinguish between different types of energy inputs. Additionally, it was recognised that the energy inputs could vary depending on the sources of fuels, electricity, raw materials, etc. These variations are due to differences in technology which are influenced by the location and the period of time under consideration. Hence, the idea of a single, universal value for representing the total energy input to the provision of a product or service was quickly found to be inappropriate. The need for transparency in recording results was established. This would not only enable details to be retained when presenting results but would also allow assumptions to be stated. It was appreciated that this would increase confidence in the exchange and use of results, as well as offering the possibility of modifying results subsequently to reflect important changes.

Unfortunately, a widely-adopted, single system for presenting the results of energy analysis was not forthcoming. Numerous diverse systems were used in practice and this continued with the evolution of energy analysis into carbon analysis. Similar problems were then encountered with the emergence of life cycle analysis. However, by this time, the need of a systematic approach to recording results was generally accepted, if only because of the considerable complexity of the results of life cycle analysis studies which consisted of inventories of inputs and outputs and lists of environmental impacts. Various methods of recording and presenting the results of life cycle analysis have been devised and applied. In particular, dedicated procedures for performing life cycle analysis, based on computer software packages, have been developed. These offer systematic means for conducting life cycle analysis calculations and, consequently, for presenting results. Additionally, these packages usually incorporate databases of results to assist with calculations. Such databases adopt established formats for containing and displaying results. These are often offered as standard methods for presenting results. However, it should be noted that there is no agreed standard method. Indeed, the established and accepted guidelines, articulated in the International Standard for life cycle analysis (Refs. 9 and 10), do not prescribe any given method and only provide examples based on clarity, detail, transparency, etc.

Despite this lack of an universal means of presenting results, it is possible to propose a method which adopts the best features of existing practice, especially within the field of life cycle analysis, and meets the needs of the current work. The basis of this method is a basic spreadsheet format for summarising results for individual products or services. An example of this, for ammonium nitrate fertiliser, is shown in Table 1. A version of the basic spreadsheet, based on Excel software, is given in Appendix A. Apart from demonstrating the features of this basic method of presenting results, the example provided in Table 1 illustrates solutions to some of the issues discussed above (see Section 2.1). The example chosen summarises details of calculations used to derive energy and carbon requirements for ammonium nitrate fertiliser which were incorporated into earlier studies of biomass production (Refs. 11 and 12). These results were based on an amalgamation of data available at that time.

The first entry in Table 1 is the specification of the functional unit designates the product or service to which the results refer. The term “functional unit” derives from life cycle analysis and refers to clear definition of the product or service under consideration (Ref. 9). The use of this term in life cycle analysis is very important since it enables results for alternative products or services to be compared in a meaningful manner. Indeed, use of the term recognises that alternatives must be compared on the basis of the equivalent function which they perform or provide. Apart from ensuring clarity, the term is useful for the energy and carbon analysis work in this project since it enables results to be recorded for either a product (for example, a bulk carrier) or a service (for example, tonne-kilometres of freight transported by a bulk carrier). In this particular example, the specification of the

Table 1 Method for Presenting the Results of Energy and Carbon Analysis of a Basic Product or Service

Specification of the Functional Unit: Bulk (unbagged) ammonium nitrate fertiliser at factory gate produced via ammonia and nitric acid from natural gas feedstock

Unit of Measurement: kg of NH_4NO_3 - see Note (a)

Relevant Location: United Kingdom - see Note (b)

Relevant Period: 1990 - see Note (b)

Contributions	Primary Energy Inputs (MJ)									Carbon Dioxide Emissions (kg CO_2)						
	Direct		Indirect		Feedstock		Total		Comments	Direct		Indirect		Total		Comments
	Value	Range	Value	Range	Value	Range	Value	Range		Value	Range	Value	Range	Value	Range	
Natural Gas	0	0	1.332	±0.130	9.675	±0.948	11.007	±0.957	Note (c)	0.474	±0.046	0.065	±0.006	0.539	±0.046	Note (f)
Fuel Oil	7.270	±0.712	2.975	±0.292	0	0	10.245	±0.770	Note (d)	0.466	±0.046	0.190	±0.019	0.656	±0.050	Note (g)
Electricity	0.327	±0.032	0.912	±0.089	0	0	1.239	±0.095	Note (e)	0	0	0.069	±0.068	0.069	±0.068	Note (h)
Other Fuels																
Chemicals																
Capital Plant																
Maintenance																
Totals	7.597	±0.713	5.219	±0.332	9.675	±0.948	22.491	±1.232		0.940	±0.065	0.324	±0.071	1.264	±0.096	

Notes

(a) 1 kg of NH_4NO_3 equals 0.35 kg N

(b) Original 1972 data for ammonium nitrate production in the United States of America (Ref. 13) updated with 1990 data (Ref. 14) with estimated ranges based on data for inorganic chemical fertiliser production in the United Kingdom in 1980 (Ref. 15).

(c) Indirect energy input derived assuming a primary energy efficiency for natural gas supply of 0.879 (Ref. 16).

(d) Direct energy input based on a boiler efficiency of 80% and indirect energy input derived assuming a primary energy efficiency for fuel oil production of 0.887 (Ref. 16).

(e) Indirect energy input derived assuming a primary energy efficiency for electricity of 0.264 (Ref. 16).

(f) Associated carbon dioxide emissions derived assuming a carbon coefficient for natural gas of 0.049 kg CO_2/MJ (Ref. 17).

(g) Associated carbon dioxide emissions derived assuming a carbon coefficient for fuel oil of 0.064 kg CO_2/MJ (Ref. 17).

(h) Associated carbon dioxide emissions derived assuming a carbon coefficient for electricity of 0.210 kg CO_2/MJ (Ref. 17).

functional unit enables the actual type of fertiliser under consideration to be stated clearly. Additionally, the functional unit indicates that the results presented refer to fertiliser available "at the factory gate". Hence, any energy inputs or carbon dioxide outputs involved in transporting the fertiliser to the end user are excluded from these results.

The second entry in Table 1 also reinforces specification of the product since it designates the units used to measure the results. In addition to stating that energy inputs are measured in MJ (10^6 joules) and CO_2 outputs are measured in kilograms of carbon dioxide (kg CO_2), this entry indicates the units used for measuring the product or service for which results are recorded. For this particular example, the results refer to fertiliser measured in terms of kilograms of ammonium nitrate (NH_4NO_3) rather than kilograms of available nitrogen (N). There are significant differences between these means of specifying the weight of fertiliser. Hence, this entry ensures that any ambiguity is avoided.

The next two entries in Table 1 specify the location and period to which the results refer. These entries are important because the amount of energy consumed and carbon dioxide released during the provision of a product or service depend on the actual technology involved. This may vary from place to place and time to time. For example, the total energy input and total CO_2 output associated with the supply of electricity is wholly dependent on the means of generation. The actual mix of power plant varies between countries and over periods of time. The same is true for any product or service and, hence, relevant information incorporated in these entries provides clarity and enables results from different sources to be distinguished properly. In this particular example, the initial data were derived from a source produced in the United States of America (Ref. 13), updated to 1990 (Ref. 14) and modified to reflect circumstances in the United Kingdom (Ref. 15). Hence, the results were considered to be acceptable equivalents for the United Kingdom in the 1990's, as required in the original studies (Refs. 11 and 12).

It will be seen from Table 1 that the primary energy inputs are grouped into four different categories; direct, indirect, feedstock and total, and CO_2 outputs are arranged in three different categories; direct, indirect and total. In this example, estimates of primary energy inputs and CO_2 outputs are provided for natural gas used as feedstock, and fuel oil and electricity used in the fertiliser plant. There are no estimates for the primary energy inputs and CO_2 outputs from the use of other (minor) fuels, the use of other chemicals, the manufacture of the capital plant and the provision of maintenance, since such data were not available at the time. The results presented for natural gas illustrate the how the issue of feedstock is addressed in this particular example. In essence, the natural gas provides a source of hydrogen which can be combined with nitrogen and oxygen in the air to produce ammonia and nitric acid which are subsequently reacted together to obtain ammonium nitrate. In the course of these reactions, CO_2 is released. Hence, there is an entry for this as a direct CO_2 output. However, this release of CO_2 does not arise as a consequence of natural gas combustion. As a result, the primary energy associated with the natural gas is recorded as an entry under feedstock. It should be noted that the indirect primary energy inputs and CO_2 outputs recorded for the natural gas, fuel oil and electricity arise from the activities associated with the production of these fuels from natural resources.

In Table 1 there are distinctions in the entries for recording primary energy inputs and carbon dioxide outputs, specified as “value” and “range”. The purpose of this is to recognise that variations may arise in primary energy inputs and associated CO_2 emission outputs for even a very specific process. Hence, an arithmetic mean may be recorded in the “value” column and the associated standard deviation will be entered into the “range” column. This would be the case for results which follow a symmetrical or normal frequency distribution. However, it must be realised that result are often represented by asymmetrical or non-normal frequency distributions. In such cases, the mode or logarithmic mean of the results may be more appropriate entries for the “value” with a statistical derived variation, such as a logarithmic interpretation of the standard deviation, for the “range”. The mathematical basis for deriving results from symmetrical and asymmetrical frequency distributions is set out in Appendix A. Since results are not expressed as single “values” but are qualified by means of their “ranges”, it is necessary to take this into account when calculating total primary energy inputs and associated CO_2 emission outputs. This can be accommodated by application of propagation of errors routines which are embedded in the Excel spreadsheet and the mathematical basis is explained in Appendix A.

2.4 Summary of Results

It should be apparent from the above description of the method of presenting results that the time and location to which results refer can have a significant effect on quoted values. There are many reasons why results may change over time, including the sources of raw materials, the type of technology adopted, and the mixture of processes involved. Clearly, the mix and sources of fuels and electricity used in the provision of products and services can have a very profound influence on subsequent energy and carbon results. This can be illustrated by information on the gross energy requirements of fuels and electricity produced in the UK between 1963 and 1996, shown in Table 2. It can be seen that significant changes have occurred over the period in question, especially in relation to the gross energy requirements for gas and electricity. These changes alone have a fundamental effect on energy and carbon results for products and services provided in the UK. It should be noted that a number of databases used in the field of energy and carbon analysis incorporate, explicitly or implicitly, results which are based on data going back as far as the 1960's. Hence, the need to update results for the current energy and carbon modelling of biomass systems is quite apparent.

Table 2 Gross Energy Requirements for Fuels and Electricity, UK 1963 – 1996

Year	Gross Energy Requirement (MJ/MJ)			
	Coal	Gas	Petroleum Products	Electricity
1963[(a)]	1.047	1.546	1.238	4.545
1968[(b)]	1.042	1.391	1.133	4.184
1972[(a)]	1.047	1.233	1.116	3.968
1974[(c)]	1.071	1.138	1.140	3.788
1984[(d)]	1.006	1.068	1.131	2.985
1996[(e)]	1.013	1.110	1.110	3.083

Notes
(a) From unpublished work in the Energy Research Group of the Open University during the 1970's.
(b) From Ref. 18.
(c) From Ref. 16.
(d) From Ref. 19.
(e) From Ref. 20.

The results summarised here cover a period around 1990. It is not possible to be precise about the year to which all results apply since it has been necessary to derive them from a variety of different sources. However, it has been intended to obtain results for prominent inputs to biomass systems, principally, from the most recent process analysis work. The selection of the prominent inputs was based on earlier work which was used to identify the most important contributions to the total energy inputs and associated CO_2 emission outputs of biomass systems based on the production of wood chips from SRC and forestry wastes and their subsequent use in electricity generation (Refs. 1 and 2). The details of this selection process are presented in Appendix B. This process has demonstrated that seven inputs contribute approximately 96% to the primary energy consumption and approximately 92% of the associated CO_2 emissions of these particular biomass systems. These inputs consist of the start-up fuel, construction and maintenance of the power plant, all uses of diesel fuel for agricultural and forestry machinery and road transport vehicles, fencing and bulk carrier manufacture. It is assumed that the biomass systems considered in Appendix B do not require the use of fertilisers and storage facilities (Ref. 2). However, an earlier study incorporated these inputs which resulted in significant contributions to primary energy consumption and associated CO_2 emissions (Ref. 1). Hence, it can be concluded that it is necessary to regard diesel fuel, fertilisers, fencing, storage facilities, and the combined components of biomass conversion plants, including cement, concrete and construction steel, as potentially important inputs for energy and carbon analysis. Consequently, process analysis is used to derive energy and carbon requirements for these specific inputs in Sections 2.4.1 to 2.4.6. Because of their diversity, subsequent results for all other biomass conversion plant components, including bulk materials such as cement, concrete and construction steel, were derived from statistical analysis based on provisional data for the UK in 1988. These results are presented in Section 2.4.7.

2.4.1 Diesel Fuel

Details of the calculation of the energy and carbon requirements for diesel fuel are summarised in Appendix C. As indicated in Table 2, the latest estimate of the gross energy requirement for petroleum products is 1.110 MJ/MJ which refers to the UK in 1996 (Ref. 20). Assuming that the gross calorific value of diesel fuel is 45.60 ± 0.20 MJ/kg (Refs. 20 and 21), then the **gross energy requirement of diesel fuel is 50.62 ± 0.22 MJ/kg**. With an average density of diesel fuel of 1.185 litres/kg (Ref. 21), the gross energy requirement of 42.72 ± 0.19 MJ/litre is obtained. Using a total emission factor of 76.70 g CO_2/MJ, which includes emissions from both fuel production and subsequent combustion (Ref. 20), produces an estimated **gross carbon requirement of diesel fuel of 3.497 ± 0.015 kg CO_2/kg**, or 2.951 ± 0.013 kg CO_2/litre. These results are recommended as the most up-to-date currently available for use with fuel consumption rates for agricultural and forestry machinery and bulk carriers involved in the growing, harvesting and transporting biomass material. Standard published sources are available for data on fuel consumption rates for agricultural machinery (Ref. 22). The most appropriate source of data on fuel consumption rates for forestry machinery, especially forwarders and chippers which are significant items of equipment, consists of a previous energy and carbon analysis study of wood-fired electricity generating systems (Ref. 2).

Bulk carriers refer to a range of road transport vehicles which can be used to transfer biomass materials for the site of harvesting to the point of use. Details of the calculation of the energy and carbon requirements for bulk carriers with payload capacities of between 14.0 tonnes and 19.5 tonnes are given in Appendix C. The estimated **energy requirement for bulk carrier transport is 1.105 ± 0.047**

MJ/tonne-kilometre and the estimated **carbon requirement for bulk carrier transport is 0.072 ± 0.003 kg CO_2/tonne-kilometre**. As shown in Appendix C, these energy and carbon requirements are composed of contributions from diesel fuel consumption, and bulk carrier manufacture, maintenance and repair. In particular, the **bulk carrier manufacture energy requirement is 0.192 ± 0.035 MJ/tonne-kilometre** and the **bulk carrier manufacture carbon requirement is 0.009 ± 0.002 kg CO_2/tonne-kilometre**. It should be noted that it is necessary to take into account the total round trip, including both outward and return journeys, when using these results to estimate the primary energy inputs and CO_2 emissions of using bulk carrier to transport biomass.

2.4.2 Fertilisers

Fertilisers are not prominent considerations for the energy and carbon modelling of wood chip production in the most recent study due to assumed agricultural and forestry practices for growing SRC and trees (Ref. 2). However, the primary energy inputs and associated CO_2 outputs of these bulk materials may be more significant in other studies of biomass production systems where fertilisers are used. The reason for this is that a number of fertilisers are relatively energy intensive and, consequently, carbon intensive. Hence, it was considered necessary to provide updated energy and carbon requirements for the most common bulk fertilisers and related chemicals, consisting of ammonium nitrate (NH_4NO_3), rock and super phosphate (P_2O_5), potash (K_2O) and lime (CaO). Details of the calculation for the energy and carbon requirements for these agricultural bulk supplies are provided in Appendix C.

Various sources of data are used to simulate the energy and carbon requirements of ammonium nitrate fertiliser production in the UK in 1996. It is assumed that natural gas provides the feedstock for ammonia production by means of the steam reforming process. In addition to feedstock, fuel and electricity consumption, the primary energy inputs and CO_2 outputs of capital plant, packaging and transportation are taken into account. This results in an **energy requirement for ammonium nitrate fertiliser of 27.8 ± 2.3 MJ/kg NH_4NO_3**. This is equivalent to an energy requirement of 79.6 ± 6.4 MJ/kg N. These estimates can be compared with results from other studies. Earlier work using older data derived an energy requirement for ammonium nitrate fertiliser, excluding packaging and delivery, of 22.5 MJ/kg NH_4NO_3 (Ref. 11). Table 1 contains the details on which this estimate is based. A number of independent studies have evaluated the primary energy inputs to ammonium nitrate fertiliser. One particular study, which explicitly incorporated the primary energy input of feedstock, obtained an energy requirement of 27.3 MJ/kg NH_4NO_3 (Ref. 22). Two other studies quote energy requirements of 12.6 MJ/kg NH_4NO_3 (Ref. 23) and 12.4 MJ/kg NH_4NO_3 (Ref. 24). These results suggest that the primary energy inputs of feedstock are not included in these particular studies.

The calculations presented in Appendix C produce a **carbon requirement for ammonium nitrate fertiliser of 1.35 ± 0.11 kg CO_2/kg NH_4NO_3**. This is equivalent to a carbon requirement of 3.9 ± 0.31 kg CO_2/kg N. It should be noted that these results assume that all CO_2 recovered during the production of this fertiliser from its raw materials is eventually released into the atmosphere. Additionally, these results include CO_2 emissions from the manufacturing of capital plant and packaging, and the provision of transport to the point of use. Consequently, these results are slightly higher that the carbon requirement of 1.26 kg CO_2/kg NH_4NO_3, obtained from earlier work (Ref. 11), with the details of the calculation illustrated here in Table 1. This earlier estimate does not include CO_2 emissions from packaging and delivery. There appear to be only a limited number of comparative results from independent studies. In particular, one life cycle analysis presents a carbon requirement for ammonium nitrate fertiliser of 0.52 kg CO_2/kg NH_4NO_3 (Ref. 23). It is suspected that CO_2 emissions associated with the use of feedstock may have been excluded from this result.

There are a number of different types of phosphate fertiliser, including rock phosphate, single superphosphate and triple super phosphate, and these can be produced by a range of different processes. The basic raw material for all these fertilisers is phosphate rock and the most prominent source of this for the UK is Morocco. The calculations presented in Appendix C are based on data from another study (Ref. 22) and assume that finished phosphate fertiliser, of any type, is produced, granulated and bagged in Morocco before shipping by sea to the UK where it is delivered to the point of use by road transport. It is also assumed that rock phosphate fertiliser contains 32% P_2O_5, that single superphosphate fertiliser contains 18% P_2O_5, and that triple superphosphate 46% P_2O_5. On this basis, the **energy requirement of rock phosphate fertiliser is 15.1 MJ/kg P_2O_5** and the **carbon requirement for rock phosphate fertiliser is 1.01 kg CO_2/kg P_2O_5**. Similarly, the **energy requirement of single superphosphate fertiliser is 16.3 MJ/kg P_2O_5** and the **carbon requirement for single superphosphate fertiliser is 1.04 kg CO_2/kg P_2O_5**. Also, the **energy requirement of triple superphosphate fertiliser is 13.6 MJ/kg P_2O_5** and the **carbon requirement for triple superphosphate fertiliser is 1.03 kg CO_2/kg P_2O_5**. Alternative studies chiefly concentrate on primary energy inputs and they do not clearly specify the type of phosphate fertiliser under consideration. However, comparable energy requirements are quoted, ranging from 15.8 MJ/kg P_2O_5 (Ref. 24) to 15.9 MJ/kg P_2O_5 (Ref. 22).

Average worldwide data are used to estimate the energy and carbon requirements of potash fertiliser produced in the UK in a granulated form, packaged and delivered to the point of use. As shown in Appendix C, this provides an **energy requirement for potash fertiliser of 8.7 MJ/kg K_2O**. The main source of data for this estimate is another study which presents an energy requirement of 12.7 MJ/kg K_2O (Ref. 22). It is noted that considerably higher primary energy inputs to packaging and transportation are assumed in this independent source. Another study quotes a more comparable energy requirement of 9.3 MJ/kg K_2O (Ref. 24). As derived in Appendix C, the **carbon requirement of potash fertiliser is 0.60 kg CO_2/kg K_2O**. There are no known comparative results from other studies.

Data used to estimate the primary energy inputs and CO_2 outputs of lime production from limestone by means of rotary kilns in the UK provide an **energy requirement for lime of 6.43 ± 0.21 MJ/kg CaO**. This estimate, which includes the primary energy input of capital plant, packaging and transport to the point of use, is somewhat higher than results of independent studies which quote energy requirements for lime of 1.05 MJ/kg CaO (Ref. 22) and 2.97 MJ/kg CaO (Ref. 24). The cause of these differences between these results is not known. The calculations in Appendix C provide a **carbon requirement for lime of 1.09 ± 0.01 kg CO_2/kg CaO**. This includes the CO_2 released during the calcination of limestone. Comparative estimates are not available from other sources.

2.4.3 Fencing

Initial work on modelling the energy and carbon budgets of wood fuel coppice systems considered the primary energy inputs and CO_2 emissions of constructing wire netting and electric fences to protect SRC plantations from rabbits and/or farm animals (Ref. 1). This provides the basic data on the materials used for standard designs of wire netting and electric fences. The subsequent calculation of updated values of the energy and carbon requirements of such fences is summarised in Appendix C. This indicates that the **wire fence energy requirement is 164 ± 61 MJ/m length of fence** and that the **wire fence carbon requirement is 7.906 ± 2.768 kg CO_2/m length of fence**. In contrast, the **electric fence energy requirement is 41 ± 12 MJ/m length of fence** and the **electric fence carbon requirement is 2.229 ± 0.524 kg CO_2/m length of fence**. In these calculations it has been assumed that all timber used for fence stakes, posts and struts consists of rough softwood produced directly from forestry operations. Hence, this is subject to minimal processing, apart from treatment with wood preservative. Only limited comparison is possible with other estimates of the energy requirements for timber. In particular, one life cycle analysis study derives an energy requirement for UK timber growing and harvesting (but excluding subsequent transport) in 1999 of 0.061 MJ/kg of green small wood (Ref. 20). The results presented in Appendix C assume an equivalent energy requirement of UK timber of 0.132 ± 0.059 MJ/kg of oven dried wood. Subsequent transport adds a further 0.372 MJ/kg of oven dried wood. Due to the basis of the life cycle analysis calculations, it is not possible to compare carbon requirements.

2.4.4 Storage Facilities

Earlier work on modelling the energy and carbon budgets of wood fuel coppice systems also examined the primary energy inputs and CO_2 emissions of constructing storage facilities for SRC wood chips (Ref. 1). In particular, a standard design for a relatively temporary barn, with a useful life of about 5 years, was formulated and this was used as a basis for updating energy and carbon requirements in Appendix C. It was assumed that such a barn would constructed using a rough softwood frame and steel cladding, with an earth floor, and concrete blocks and wire netting for the internal wood chip storage space. This resulted in an **energy requirement for the temporary barn of 409,200 ± 19,000 MJ** and a **carbon requirement for the temporary barn of 18,840 ± 850 kg CO_2**. The standard design was also used to simulate the materials requirements for a permanent barn, with a useful life of about 25 years. Such a barn was assumed to consist of a steelwork frame with steel cladding, a concrete floor, and concrete blocks and wire netting for internal wood chip storage space. As a consequence, the **energy requirement of the permanent barn is 800,900 ± 33,300 MJ** and the **carbon requirement of the permanent barn is 38,880 ± 1,500 kg CO_2**. It can be seen that, from the perspective of primary energy consumption and associated CO_2 emissions, the permanent barn is a more effective option for the storage of biomass relative to the temporary barn.

2.4.5 Cement and Concrete

It is difficult to obtain basic data on the operation of individual cement manufacturing plants in the UK as such information is generally regarded as confidential. Hence, there are problems in attempting to derive representative energy and carbon requirements for cement, especially in terms of their average values and ranges.

Consequently, national statistical data appears to be the most reliable basis for calculating primary energy inputs and CO_2 outputs for UK cement production. In particular, national input-output tables and related statistics can be used to obtain results (see Section 2.4.7 and Appendix D). On this basis, provisional results for 1988 indicate that the **energy requirement of Portland cement is 6.0 MJ/kg** and the **carbon requirement of Portland cement is 0.382 kg CO_2/kg**. This energy requirement can be compared with earlier estimates for cement production in the UK which revealed a range from 6.4 MJ/kg to 7.3 MJ/kg, or 6.8 ± 0.5 MJ/kg (Ref. 25). This suggests that the results from national statistics are appropriate. It should be noted that these results include the CO_2 emitted during the calcination process in accordance with recommended procedures (Ref. 26).

There is a considerable variation in the energy and carbon requirements for aggregates used in concrete. This is partly due to differences in aggregate types, sources and methods of production. Earlier work demonstrated energy requirements for natural aggregates ranging from 0.03 MJ/kg to 0.30 MJ/kg (Ref. 27). These results are somewhat lower than those results derived from national input-output tables and related statistics (see Section 2.4.7 and Appendix D). For example, the **energy requirement of sand and gravel is 0.31 MJ/kg** and the **carbon requirement of sand and gravel is 0.012 kg CO_2/kg**. Additionally, the **energy requirement of concrete aggregates is 0.49 MJ/kg** and the **carbon requirement of concrete aggregates is 0.019 kg CO_2/kg**. It should be noted that these estimates include the primary energy inputs and CO_2 outputs of transport and, hence, may be more suitable for subsequent use. The energy and carbon requirements of concrete depend on the actual mix of cement, aggregate and water. However, results from national input-output tables and related statistics give an **energy requirement for ready mixed concrete of 1.1 MJ/kg** and a **carbon requirement for ready mixed concrete of 0.047 kg CO_2/kg**. These estimates can be used as general averages when the specific grade of concrete is not known.

2.4.6 Construction Steel

Considerable variations arise in the energy and carbon requirements of construction steel due to the potential range of components which can be included in this broad description. For this reason, results derived from national input-output tables and related statistics (see Section 2.4.7. and Appendix D) can be regarded as more representative than those which might be obtained from the analysis of specific steel works. On this basis, the **energy requirement of mild steel reinforcing bars is 42.9 ± 4.5 MJ/kg** and the **carbon requirement of mild steel reinforcing bars is 1.938 ± 0.203 kg CO_2/kg**. This energy requirement can be compared with a value for steel reinforcing bars of 39.5 MJ/kg obtained in an earlier study (Ref. 28). Similarly, the **energy requirement of steel sheet is 40.9 ± 2.1 MJ/kg** and the **carbon requirement of steel sheet is 1.849 ± 0.094 kg CO_2/kg**. The earlier study derived and energy requirement for steel sheet of 38.0 MJ/kg (Ref. 28). Finally, the **energy requirement of structural steelwork is 31.7 ± 3.9 MJ/kg** and the **carbon requirement of structural steelwork is 1.434 ± 0.177 kg CO_2/kg**. For comparison, another study gave the energy requirement of heavy steel fabrications of 34.2 MJ/kg (Ref. 29).

2.4.7 Biomass Conversion Plant Components

Due to the diversity and relative complexity of the various items of equipment and machinery which comprise any biomass conversion plant, it is more appropriate to use the results of national input-output tables and statistics for subsequent energy and carbon modelling. Very considerable information would be needed in any attempt to calculate the energy and carbon requirements of biomass conversion plant components by means of process analysis. Even if this were possible, the results would probably only be relevant to one particular manufacturing process or site. Instead, statistical analysis enables results to be obtained more easily. Additionally, these results can be regarded as statistically-representative of overall production for the UK. However, there is some reduction in the accuracy of results and the application of general energy and carbon requirements for any given collection of manufacturers, or "Industry Groups", must be treated with a degree of caution.

With these considerations in mind, provisional energy and carbon intensities were estimated for the UK in 1988. This involved applying procedures developed previously for analysis of the 1984 input-output tables for the UK (Ref. 19). In particular, energy and carbon intensities were derived for the following Industry Groups; 10 Iron and Steel, 11 Aluminium, 12 Other Non-Ferrous Metals, 13 Extraction of Stone, 15 Cement, 16 Concrete, 18 Refractory and Ceramic Goods, 29 Metal Castings, 33 Industrial Plant and Steelwork, 38 Process Machinery, 40 Mechanical Power Transmission Equipment, 41 Other Machinery, 44 Insulated Wires and Cables, 45 Basic Electrical Equipment, 46 Industrial Electrical Equipment, 48 Electronic Components, and 88 Construction. Energy and carbon intensities were converted to energy and carbon requirements, respectively, by using price per unit weight data obtained from sales and trade statistics by means of methods developed during earlier work (Ref. 8). Subsequent results are presented in Appendix D.

3. BIOMASS CONVERSION TECHNOLOGIES

3.1 General Procedures

The initial list of biomass conversion technologies selected for study consisted of a demonstration scale wood gasification power only plant, a large scale wood gasification power only plant, a modular wood gasification combined heat and power plant, a small-scale biomass pyrolysis power only plant, a large-scale biomass pyrolysis power only plant, a large-scale straw burning power only plant, a small-scale wood burning heat only plant, a large-scale wood burning heat only plant, and a large-scale rape methyl ester liquid biofuel plant. However, during the course of the data collection for energy and carbon analysis, it became apparent that this list would have to be modified. In particular, relevant information could not be supplied on certain biomass conversion technologies because of issue of commercial sensitivity, etc. However, in some instances, information became available on plants not included in the original list. Hence, the following biomass conversion technologies were examined here:

demonstration-scale wood gasification power only plants,

a large-scale wood gasification power only plant,

a modular wood gasification combined heat and power plant, a large-scale wood pyrolysis power only plant,

a small-scale wood burning heat only plant,

a large-scale wood burning heat only plant, and

a large-scale rape methyl ester (RME) liquid biofuel plant.

3.2 Construction

The data required to perform energy and carbon analyses of the construction of these biomass conversion technologies were derived from a variety of sources. In particular, primary data were obtained from manufacturers and developers. This usually consisted of detailed information on components, dimensions, specifications and, occasionally, weights from design and plan data, and actual inventories. In certain circumstances, such primary data were supplemented with generic information and general assumptions. This was mainly necessary in cases where there was inadequate or missing data. Scale rules also had to be applied in some cases to derive estimates for larger items of equipment. By such means, comprehensive weight inventories were assembled which enabled primary energy inputs and associated CO_2 outputs to be calculated using a standard Excel spreadsheet.

Although the standard Excel spreadsheet, presented in Appendix A, provides a suitable means of recording and presenting the results of energy and carbon analysis for specific products and services, further modification was required for its use in calculating primary energy inputs and associated CO_2 outputs for the construction of biomass conversion plants. Additional entries need to be considered to ensure adequate coverage of data and transparency of results. The basic structure is illustrated in Table 3 which provides an example of the method of presenting the results of the energy analysis of the construction of a biomass conversion plant. This illustration is based on the construction inventory of a 30.0 MW(e) wood gasification combined cycle gas turbine power plant which was examined in an earlier study (Ref. 2). The use of cost data and carbon intensities and the effect of ranges of values on results are not demonstrated in Table 3 due to the nature of this earlier study. Each item of the power plant is identified in the first main column, weight and cost inventory data for the power plant are recorded in the second and third main columns, respectively, appropriate multipliers, in the form of energy requirements and energy intensities, are summarised in the fourth and fifth main columns, respectively, and results, in the form of the primary energy input, are presented in the final column. Sub-columns are provided for entering values and ranges so that variations can be determined by means of the same propagation of errors routines incorporated in the basic spreadsheet described earlier.

Actual analysis of data collected on the construction of biomass conversion technologies was undertaken by recording the weights of specified components in the spreadsheet. Appropriate multipliers, in the form of energy and carbon requirements, were then chosen from the database to represent these components or, in certain instances, their nearest equivalents. Where necessary, this analysis was supplemented with cost data and relevant energy and carbon intensities. Detailed spreadsheets were formulated summarising all the basic data and subsequent results in a comprehensive and transparent manner. Depending on the

Table 3 Method for Presenting the Results of the Energy and Carbon Analysis of Power Plant Construction

<table>
<tr><td colspan="11">Functional Unit: 30.0 MW(e) net wood gasification combined cycle gas turbine power plant</td></tr>
<tr><td colspan="11">Unit of Measurement: MW net electrical installed capacity</td></tr>
<tr><td colspan="11">Relevant Location: United Kingdom</td></tr>
<tr><td colspan="11">Relevant Period: 2000</td></tr>
<tr><td rowspan="2">Item</td><td colspan="2">Weight (tonnes)</td><td colspan="2">Cost (£)</td><td colspan="2">Energy Requirement (MJ/tonne)</td><td colspan="2">Energy Intensity (MJ/£)</td><td colspan="2">Primary Energy Input (GJ)</td></tr>
<tr><td>Value</td><td>Range</td><td>Value</td><td>Range</td><td>Value</td><td>Range</td><td>Value</td><td>Range</td><td>Value</td><td>Range</td></tr>
<tr><td>Concrete</td><td>9605</td><td></td><td></td><td></td><td>1090</td><td></td><td></td><td></td><td>10469</td><td></td></tr>
<tr><td>Reinforcing Bar</td><td>960</td><td></td><td></td><td></td><td>30000</td><td></td><td></td><td></td><td>28812</td><td></td></tr>
<tr><td>Building Steelwork</td><td>105</td><td></td><td></td><td></td><td>28000</td><td></td><td></td><td></td><td>2940</td><td></td></tr>
<tr><td>Gasifier</td><td>330</td><td></td><td></td><td></td><td>122000</td><td></td><td></td><td></td><td>40260</td><td></td></tr>
<tr><td>Gas Clean-up System</td><td>36</td><td></td><td></td><td></td><td>122000</td><td></td><td></td><td></td><td>4392</td><td></td></tr>
<tr><td>Turbines</td><td>77</td><td></td><td></td><td></td><td>158000</td><td></td><td></td><td></td><td>12166</td><td></td></tr>
<tr><td>Generators</td><td>77</td><td></td><td></td><td></td><td>78000</td><td></td><td></td><td></td><td>6006</td><td></td></tr>
<tr><td>Air Cooled Condenser</td><td>300</td><td></td><td></td><td></td><td>122000</td><td></td><td></td><td></td><td>36600</td><td></td></tr>
<tr><td>HRSG</td><td>50</td><td></td><td></td><td></td><td>122000</td><td></td><td></td><td></td><td>6100</td><td></td></tr>
<tr><td>Switchgear</td><td>142</td><td></td><td></td><td></td><td>82000</td><td></td><td></td><td></td><td>11644</td><td></td></tr>
<tr><td>Other Equipment</td><td>1113</td><td></td><td></td><td></td><td>116700</td><td></td><td></td><td></td><td>129889</td><td></td></tr>
<tr><td>Construction</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td>14464</td><td></td></tr>
<tr><td>Totals</td><td>12795</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td>303742</td><td></td></tr>
</table>

nature of any confidentiality agreements governing the supply of the original data, these detailed spreadsheet were transferred, in electronic format, to ETSU. Since some of the original data cannot be released publicly for reasons of commercial sensitivity, aggregated spreadsheets were derived from these detailed spreadsheets. In these aggregated spreadsheets, data and results are grouped together into a limited number of categories, as presented for each biomass conversion technology in Sections 3.2.1 to 3.2.7.

3.2.1 Demonstration-Scale Wood Gasification Power Only Plant

Inquiries to Suffolk Biomass Power Ltd, a wholly-owned subsidiary of Primergy Europe Ltd, about data collection began during the planning process for their 5.5 MW(e) wood gasification power only plant. Hence, it was only possible to obtain limited information based on estimates for this plant which will incorporate three horizontal rotary kiln gasifiers to supply nine gas engines for power generation. In order to assist the data collection procedures, a confidentiality agreement was negotiated and signed on 25 January 2001. This enabled basic data to be provided by Mr. M. McGawley, Project Advisor. Initially, aggregated cost data were supplied and this enabled preliminary results to be derived using energy and carbon intensities. These results are summarised in Table 4 which indicates that the total energy input is approximately **227,000 GJ** and the total CO_2 output is approximately **10,800 tonnes**. From past experience, it is normally expected that results from energy and carbon analysis based entirely on cost data would over-estimate actual primary energy inputs and associated CO_2 outputs. Subsequently, energy and carbon analysis was performed on weight data derived from further information sent by Mr. M. McGawley. This information consisted of site plans, schedules of equipment, equipment lists, weight estimates, etc. Unfortunately, complete information was not available at this stage in the planning process. Hence, it was necessary to estimate and extrapolate weights for some components from generic sources. This also required the use of a number of basic simplifying assumptions in preparing the detailed spreadsheet which contained entries for

Table 4 Results of Energy and Carbon Analysis for a 5.5 MW(e) Wood Gasification Power Only Plant Based on Cost Data

Description of Functional Unit: Wood Gasification Power Only Plant				
Unit of Measurement: 5.5 MW(e) net output				
Relevant Location: United Kingdom				
Relevant Period: 2000				
Component	Energy Input (GJ)		Carbon Dioxide Output (tonnes CO2)	
	Approximate	Percent	Approximate	Percent
Foundations and Structure	17950	*8*	793	*7*
Wood Handling and Supply System	20142	*9*	991	*9*
Gasification Plant	30360	*13*	1415	*13*
Gas Cleaning Plant	8052	*4*	375	*3*
Power Generation Plant	90854	*40*	4318	*40*
Heat Recovery and Balance of Plant	3861	*2*	180	*2*
Mechanical Installation	24384	*11*	1200	*11*
Electrics and Instrumentation	31639	*14*	1504	*14*
Totals	**227242**		**10776**	

102 individual components. Consequently, the results summarised in Table 5, reflect best available current "as planned" rather than "as built" information. As shown in Table 5,

Table 5 Results of Energy and Carbon Analysis for a 5.5 MW(e) Wood Gasification Power Only Plant Based on Weight Data

Description of Functional Unit:	Wood Gasification Power Only Plant						
Unit of Measurement:	5.5 MW(e) net output						
Relevant Location:	United Kingdom						
Relevant Period:	1999 – 2000						
Component	Weight (tonnes)	Energy Input (GJ)			Carbon Dioxide Output (tonnes CO2)		
		Average	Range	Percent	Average	Range	Percent
Foundations	13326	16496	675	*10*	711	30	*9*
Structure	509	8201	702	*5*	384	32	*5*
Wood Reception Area	43	5857	2046	*4*	431	120	*5*
Main Wood Store	26	3997	1407	*2*	314	87	*4*
Wood Drying Plant	47	10326	1113	*6*	491	54	*6*
Wood Buffer	11	3507	686	*2*	169	34	*2*
Gasification Plant	134	28893	4644	*18*	1475	207	*18*
Gas Cleaning Plant	69	12368	1296	*8*	578	61	*7*
Power Generation Plant	343	51313	3338	*32*	2406	154	*30*
Water Treatment Plant	22	5786	1052	*4*	279	51	*3*
Switchgear Yard	37	7781	2716	*5*	375	130	*5*
Miscellaneous	4	455	92	*0*	21	4	*0*
Construction Work		5269	0	*3*	405	0	*5*
Totals	**14571**	**160249**	**7191**		**8039**	**343**	

the total estimated weight of the power plant is approximately **15,000 tonnes**, with the majority of this being accounted for by foundations. The total primary energy input of construction is approximately **160,000 ± 7,000 GJ** and the associated CO_2 output from construction is approximately **8,000 ± 300 tonnes**. These estimates based on weight data are comparable with but less than those derived from cost data. Such relatively small differences between results obtained from these different methods are unusual. Only limited comparisons can be made between the results in Tables 4 and 5 due to differences in the aggregation of power plant components. However, it is interesting to note that the results obtained from cost and weight data for the gasification plant are very similar. Using cost data, relatively lower estimates are produced for the foundations, structure, and wood handling and supply system, whereas higher estimates are obtained for the power generation plant and all the remaining components. Generally, results derived from weight data should be regarded as more reliable. On this basis, Table 5 indicates that the most prominent contribution to the total primary energy input and associated CO_2 output is the power generation plant followed by the gasification plant. Together, these account for 50% of the total primary energy input and 48% of the associated CO_2 output.

The 8.0 MW(e) wood gasification power only plant, then under construction by ARBRE Energy Ltd, is a joint venture between First Renewables Ltd (89% interest), a wholly owned subsidiary of Kelda Group plc, and TPS Termiska Processer AB (11%). The combined cycle power plant has an air blown circulating fluidised bed gasifier and tar cracker which supplies a gas turbine with heat recovery to drive a steam turbine. An initial meeting to collect information for the energy and carbon analysis was held on-site, near Eggborough in North Yorkshire, United Kingdom, on 6 September 2000. Basic details of this pilot plant were explained by Mr. A. Weekes, the Environmental Engineer, and possible arrangements for accessing relevant data were discussed. To assist this process, a confidentiality agreement was completed on 28 February 2001. Subsequent on-site data collection activities took place on 12 and 13 March 2001. It should be noted that since the pilot plant was being completed and prepared for commissioning at the time, the data accessed consisted mainly of "as built" information rather than "as planned" estimates. Details were discussed with Mr. A. Weekes and various documents were consulted, including layouts, site plans, initial specifications, work schedules, equipment lists, manuals, etc. A member of the Quality Control Office, Mr. W. Smith, provided guidance with the quantity surveying documentation library. Considerable information was obtained on component weights and other data which enabled weights to be estimated. Mr. A. Weekes assisted with further comments, clarification and feedback during the interpretation of this information and during following analysis. As part of this analysis, a detailed spreadsheet was prepared which included 166 individual entries for plant components. The aggregated results of this analysis are summarised in Table 6. It was estimated that the total weight of this plant is

Table 6 Results of Energy and Carbon Analysis for a 8.0 MW(e) Wood Gasification Power Only Plant

Description of Functional Unit:	Wood Gasification Power Only Plant						
Unit of Measurement:	8.0 MW(e) net output						
Relevant Location:	United Kingdom						
Relevant Period:	1999 – 2000						
Component	Weight (tonnes)	Energy Input (GJ)			Carbon Dioxide Output (tonnes CO2)		
		Average	Range	Percent	Average	Range	Percent
Foundations	3597	5199	246	*3*	226	11	*2*
Structure	449	12521	1171	*6*	579	53	*6*
Wood Reception Area	17	1141	342	*1*	53	16	*1*
Main Wood Store	10	872	213	*0*	40	10	*0*
Wood Drying Plant	101	18010	1170	*9*	859	91	*9*
Wood Day Bins	30	7329	2772	*4*	145	36	*2*
Gasification Plant	409	27508	2068	*14*	1241	97	*14*
Cracking Plant	360	14417	1223	*7*	621	59	*7*
Gas Cooling Plant	53	16772	2631	*8*	783	123	*9*
Gas Purification Plant	42	5230	649	*3*	238	29	*3*
Power Generation Plant	391	70835	12605	*36*	3301	669	*36*
Switchgear Yard	45	8251	3068	*4*	399	147	*4*
Miscellaneous	25	2873	209	*1*	132	9	*1*
Construction Work	0	6493	0	*3*	457	0	*5*
Totals	**5529**	**197451**	**13860**		**9074**	**715**	

approximately **5,500 tonnes**, that the total primary energy input for the construction was approximately **197,000 ± 14,000 GJ** and that the associated CO_2 output from construction was approximately **9,100 ± 700 tonnes**. It can be seen from Table 6 that the foundations make the greatest contribution to the total weight of the plant, whereas the most prominent contributions to the total energy input and CO_2 output arises from the power generation plant, followed by the gasification plant, which account for 50% of these totals.

3.2.2 Large-Scale Wood Gasification Power Only Plant

An indication of the primary energy input and associated CO_2 output for the manufacture and construction of a large-scale wood gasification power only plant was derived from scaling up from the 8.0 MW(e) plant under construction by ARBRE Energy Ltd (see Section 3.2.1). Possible approaches to scaling were discussed briefly with Mr. A. Weekes, the Environmental Engineer of First Renewables Ltd. Based on suggestions received and judgements about the nature of likely design choices for a 30.0 MW(e) wood gasification power only plant, scaling relationships were formulated. In general, it was assumed that the weights of the construction and structural components and the main components of the gasification, cracking, gas cooling and gas purification plants could be scaled up from the pilot plant design using suitable power rules. It was advised that two gas turbines and one steam turbine might be incorporated into the power generation plant. Assumptions were made concerning the ratings of these turbines and their weights were scaled by means of appropriate power rules from those of the turbines in the demonstration-scale plant. Most of the remaining components were considered to be essentially modular so that multiple units of the pilot plant components were assumed in the weight calculations. As in the case of the pilot plant, a detailed spreadsheet for the large-scale wood gasification power only plant was prepared which included 166 individual entries for plant components. Table 7 illustrates the aggregated results of this analysis. It was estimated that the total weight of the large-scale wood gasification power only plant would be approximately **12,600 tonnes**, that the total

Table 7 Results of Energy and Carbon Analysis for a 30.0 MW(e) Wood Gasification Power Only Plant

Description of Functional Unit:	Wood Gasification Power Only Plant						
Unit of Measurement:	30.0 MW(e) net output						
Relevant Location:	United Kingdom						
Relevant Period:	2001						
Component	Weight (tonnes)	Energy Input (GJ)			Carbon Dioxide Output (tonnes CO2)		
		Average	Range	Percent	Average	Range	Percent
Foundations	8430	11946	563	*2*	519	25	*2*
Structure	322	9152	311	*2*	441	14	*2*
Wood Reception Area	52	3062	946	*1*	142	44	*1*
Main Wood Store	29	2133	577	*1*	99	27	*0*
Wood Drying Plant	300	50075	4023	*10*	2389	204	*11*
Wood Day Bins	120	29315	11090	*6*	582	146	*3*
Gasification Plant	991	60540	4565	*13*	2730	216	*13*
Cracking Plant	870	33233	2825	*7*	1423	136	*7*
Gas Cooling Plant	129	29759	5244	*6*	1384	244	*6*
Gas Purification Plant	103	12844	1574	*3*	586	71	*3*
Power Generation Plant	1052	183208	53517	*38*	8392	2408	*38*
Switchgear Yard	180	35446	12630	*7*	1711	604	*8*
Miscellaneous	60	7006	509	*1*	321	23	*1*
Construction Work	0	16638	0	*3*	1153	0	*5*
Totals	**12638**	**483620**	**56775**		**21817**	**2522**	

primary energy input would be approximately **484,000 ± 57,000 GJ** and that the associated CO_2 output would be approximately **21,800 ± 2,500 tonnes**. In similarity with the pilot plant, it can be seen from Table 7 that the foundations account for greatest contribution to the total weight of the large-scale plant, whereas the most prominent contribution to the total energy input and CO_2 output is associated with the power generation plant. In similarity with the pilot plant, the next most prominent contributions are from the gasification plant and then the wood drying plant. Together these contributions account for between 61% and 62% of the total energy input and CO_2 output.

3.2.3 Modular Wood Gasification Combined Heat and Power Plant

Contact was established with Mr. R. McLellan, Manager Gasification, of Wellman Process Engineering Ltd at an early stage in this work and negotiations took place to create a basis for obtaining relevant information for the energy and carbon analysis of the modular design for a 2.5 MW(e) wood gasification combined heat and power plant. In its basic modular form, this design consists of an updraught fixed bed gasifier and cracker which supplies four gas engines with heat recovery for process, space and/or water heating purposes. A confidentiality agreement was completed on 14 December 2000 to enable information to be collected by means of the inspection of plans, manuals and related information during an on-site visit to the offices of Wellman Process Engineering Ltd at Furnace Green, Oldbury, West Midlands. A particularly important source of basic information was a report on the modular design of this wood gasification plant (Ref. 30). Weight data were derived from actual figures supplemented with estimates based on specifications, dimensions, etc. A limited amount of generic weight data was used to supplement this basic information. Additionally, information on the weight of the Jenbacher gas engines, which can be incorporated into this design or replaced by Caterpillar gas engines, was supplied by Mr. H. Rees, the Proposals Manager of Clarke Energy. As such, the results of energy and carbon analysis represent the "as designed" version of the wood gasification plant in its basic modular form. Initial results were produced by means of a detailed spreadsheet which included entries for 86 individual components. The aggregated version of these results is given in Table 8. This shows that the estimated total weight of the modular plant is approximately **1,200 tonnes** with the largest contribution arising from the foundations. The primary energy input to plant construction is approximately **58,000 ± 7,000 GJ** and the associated CO_2 output is approximately **2,800 ± 200 tonnes**. It will be seen that the most prominent contribution to both the total primary energy input and associated CO_2 output is provided by the wood handling and supply system, followed by the cracker and hot gas process plant and the power generation plant. Combined together, these components contribute about 70% to the total primary energy input and associated CO_2 output. It will be noted that the gasification plant only accounts for 5% of these totals.

Table 8 Results of Energy and Carbon Analysis for a 2.5 MW(e) Wood Gasification Combined Heat and Power Plant

Description of Functional Unit:	Wood Gasification Combined Heat and Power Plant						
Unit of Measurement:	2.5 MW(e) net output						
Relevant Location:	United Kingdom						
Relevant Period:	1999 – 2000						
Component	Weight (tonnes)	Energy Input (GJ)			Carbon Dioxide Output (tonnes CO2)		
		Average	Range	Percent	Average	Range	Percent
Foundations	684	832	41	*1*	36	2	*1*
Structure	86	3185	177	*5*	144	8	*5*
Wood Handling and Supply System	140	18769	5849	*32*	894	83	*32*
Gasifier Wood Feed System	9	5209	964	*9*	255	34	*9*
Gasification Plant	41	2907	386	*5*	133	18	*5*
Cracker and Hot Gas Process Plant	146	16375	3070	*28*	758	143	*27*
Power Generation Plant	46	5768	0	*10*	274	0	*10*
Switchgear Yard	17	3458	1616	*6*	167	77	*6*
Construction Work		1921	234	*3*	141	10	*5*
Totals	**1169**	**58424**	**6886**		**2802**	**187**	

3.2.4 Large-Scale Biomass Pyrolysis Power Only Plant

Relevant information on the components for a 20 MW(e) biomass pyrolysis power only plant was provided by Dr. A. C. Bowles of Border Biofuels Ltd during the design and planning of such developments in the United Kingdom. This information, which was supplied between 19 January and 14 March 2001, consisted of plant schematics and estimates of selected plant components. Unfortunately, it was not possible to obtain complete details at this stage development. Consequently, it was necessary to supplement actual data with estimates based on broad interpretations of plant components, general assumptions and generic scaling relationships. Therefore, the results presented in Table 9 should be regarded as somewhat approximate and generally representative of an "as planned" development. Table 9 indicates that the total weight of the power plant is estimated as approximately **33,000 tonnes**, of which the majority is accounted for by the foundations and structure. The total primary energy input to the manufacture of the components and the construction of the plant is approximately **421,000 ± 39,000 GJ** and the associated CO_2 output is approximately **20,000 ± 2,000 tonnes**. The most significant contributions to both the primary energy input and associated CO_2 output, in order of prominence, are the power generation plant, the structure, the biomass drying plant and the pyrolysis plant. Combined together, these components account for over 80% of the total primary energy input and associated CO_2 output.

Table 9 <u>Results of Energy and Carbon Analysis for a 20.0 MW(e) Biomass Pyrolysis Power Only Plant</u>

Description of Functional Unit: Biomass Pyrolysis Power Only Plant							
Unit of Measurement:	20.0 MW(e) net						
Relevant Location:	United Kingdom						
Relevant Period:	2001						
Component	Weight (tonnes)	Energy Input (GJ)			Carbon Dioxide Output (tonnes CO2)		
		Average	Range	Percent	Average	Range	Percent
Foundations	15235	21483	1035	*5*	932	47	*5*
Structure	15525	76615	5853	*18*	3432	264	*17*
Biomass Reception Area	131	14385	5059	*3*	667	235	*3*
Biomass Store	3	624	156	*0*	29	7	*0*
Biomass Drying Plant	612	71055	462	*17*	3304	21	*17*
Pyrolysis Plant	563	64376	9725	*15*	2992	450	*15*
Power Generation Plant	889	134322	36147	*32*	6291	1738	*32*
Switchgear Yard	130	24779	8451	*6*	1194	439	*6*
Construction Work	0	13860	0	*3*	999	0	*5*
Total	**33088**	**421499**	**39163**		**19840**	**1882**	

3.2.5 Small-Scale Wood Burning Heat Only Plant

Data for the energy and carbon analysis of a small-scale wood burning heat only plant were collected from an installation which provides the space and water heating requirements of an office and visitors' centre. This installation consists of a Talbotts Model C1 combustion plant with a net heat output rating of 50.0 kW(t). The boiler plant, incorporating a furnace and boiler, is supplied by wood chip by means of screw feed machinery from a hopper. The plant is located within a small building which has a concrete base, breezeblock walls and a wood and felt roof. Associated equipment, such as a mild steel chimney, filter system, hot water storage tank, pipework and pump, and an auxiliary heat reject system, were included this analysis. Data collection involved inspecting all items of equipment and measuring dimension of all relevant items during a site visit on 13 March 2001. The weights of most items were calculated from these measurements, by making assumptions about their design, composition and density. Specifications, including weight data, for the combustion plant were obtained from the Talbotts website (Ref. 31). As shown in Table 10, it was estimated that the total weight of the plant is approximately **28 tonnes**, with the majority of this accounted for by the foundations and the structure, which includes the wood chip hopper and supports. The total primary energy input to construction is approximately **710 ± 80 GJ** and the associated CO_2 output is approximately **34 ± 4 tonnes**. The boiler plant, followed by the structure, form the most prominent contributions to the total primary energy input and the associated CO_2 output, totalling between 59% to 56% and 26%, respectively.

Table 10 Results of Energy and Carbon Analysis for a 50.0 kW(t) Wood Burning Heat Only Plant

Description of Functional Unit:	Wood Burning Heat Only Plant
Unit of Measurement:	50 kW(t) net output
Relevant Location:	United Kingdom
Relevant Period:	2000

Component	Weight (tonnes)	Energy Input (GJ)			Carbon Dioxide Output (tonnes CO2)		
		Average	Range	Percent	Average	Range	Percent
Foundations	15.000	16	1	*2*	1	1	*3*
Structure	11.040	181	68	*26*	9	3	*26*
Wood Store	0.1400	72	8	*10*	3	1	*9*
Boiler Plant	2.1885	416	44	*59*	19	2	*56*
Construction Work		23	3	3	2		6
Totals	**28.3685**	**708**	**81**		**34**	**4**	

3.2.6 Large-Scale Wood Burning Heat Only Plant

The chosen example of a large-scale wood burning heat only plant was the heat source for a biomass district heating scheme in Furth bei Landshut, Bavaria, Germany. This scheme, which provides space and water heating for a rural community, was completed in 1998 and is operated by the Biomasseheizwerk Furth GmbH and Co KG. The main heat source consists of a 800 kW(t) step-grate biomass furnace and boiler which uses chipped wood and similar materials from the surrounding woods, forests, farms and houses. A 1,400 kW(t) oil-fired boiler is available for meeting peak heating demands during the winter. The scheme incorporates 244 m^2 of solar panels on the roof of the wood store and boiler plant, mainly to supply water heating demands during the summer. For the purposes of this particular study, the oil-fired boiler, the solar panels and the district heating network were excluded from this analysis. Basic data were collected during a site visit on 19 June 2001 which was organised by Bürgermeister D. Gewies and Mr. R. Fahle of Soliz GmbH.. Further information was provided by a report produced by the Centrales Agrar-Rohstoff Marketing- und Entwickslungs Netzwerk in Rimpar, Germany (Ref. 32). In addition to technical data, this report also contained costings which were used in the analysis of the boiler plant pipework. Weight data for the biomass boiler were supplied by Mr. W. Kohlbach of Fa. Kohlbach of Wolfberg in Austria. An estimated weight breakdown was assembled from these sources of information. The assumed accuracy of the weight estimates was ± 20%, reflecting the approximations used in the process of estimation. The total weight of this large-scale wood burning heat only plant was estimated to be approximately **970 tonnes**, of which the foundations comprise the largest contribution. The estimated primary energy input and associated CO_2 output for the manufacture and construction of this plant is approximately **6,100 ± 500 GJ** and approximately **280 ± 20 tonnes** of CO_2, respectively. The boiler plant provides the greatest contribution to the primary energy input and associated CO_2 output of 75% and 80%, respectively.

Table 11 Results of Energy and Carbon Analysis for a 800.0 kW(t) Wood Burning Heat Only Plant

Description of Functional Unit:	Wood Burning Heat Only Plant						
Unit of Measurement:	800.0 kW(t) net output						
Relevant Location:	Germany						
Relevant Period:	1998						
Component	Weight (tonnes)	Energy Input (GJ)			Carbon Dioxide Output (tonnes CO2)		
		Average	Range	Percent	Average	Range	Percent
Foundations	726.0	584	35	*10*	20	1	*7*
Structure	225.7	494	37	*8*	22	2	*8*
Wood Store	0.6	242	56	*4*	6	1	*2*
Boiler Plant	16.7	4574	454	*75*	222	22	*80*
Construction Work		200	0	*3*	9	0	*3*
Total	**969.0**	**6094**	**460**		**279**	**22**	

3.2.7 Large-Scale Rape Methyl Ester Liquid Biofuel Plant

Various small-scale plants have been designed and built to produce liquid biofuel from a range of biomass sources, mainly consisting of vegetable oils and animal oils. However, relatively large-scale plants are less common. Hence, it was necessary to combine information from a number of different sources in order to derive an estimated weight breakdown for subsequent energy and carbon analysis of a hypothetical large-scale rape methyl ester (RME) liquid biofuel plant. The most important source of data available was for a pilot plant, with a production capacity of 40,000 tonne of biodiesel per year, which is being built by ENERGEA Umwelttechnologie GmbH at Zistersdorf in Austria. Basic information on this plant and weights for specific items of equipment were provided by Ms. B. Oman of ENERGEA Umwelttechnologie GmbH. The weights of certain components had to be estimated from very limited sources of data and assumed accuracies of ± 20% reflect this. This plant has been designed to produce biodiesel from vegetable oils and animal fats by means of the ENERGEA continuous transesterification and esterification processes. As designed, it would seem that vegetable oils and animal fats will be supplied to this pilot plant from elsewhere. Hence, to simulate a complete large-scale RME liquid biofuel plant, it was necessary to incorporate an oilseed milling plant with adequate capacity to provide natural oil for biodiesel production. A mass balance calculation for natural oil production was undertaken by Mr. R. Taylor of De Smet Rosedowns who also estimated the total weight of the milling plant, consisting of equipment such as a cleaner, mill, rolls, cooker, press, filter, and associated conveyors, pipework and pumps. An accuracy of ± 25% was allocated to this weight estimate. The results of combining this information together to simulate a complete large-scale RME liquid biofuel plant are summarised in Table 12. The estimated total weight of the plant is approximately **3,600 ± 300 tonnes**, of which the majority is accounted for by the foundations. The total primary energy input and associated CO_2 output for the manufacture and construction of this plant are found to be approximately **131,000 ± 24,000 GJ** and **6,300 ± 1,100 tonnes** of CO_2, respectively. The main contribution to both these totals is due to the oilseed milling plant which amount to 70% and 68%, respectively. However, it should be noted that, in addition to the approximate nature of the estimated weight for this plant, it was necessary to use general energy and carbon requirements for

Table 12 Results of Energy and Carbon Analysis for a 40,000 tonne per year Rape Methyl Ester Liquid Biofuel Plant

Description of Functional Unit:	Rape Methyl Ester Liquid Biofuel Plant						
Unit of Measurement:	40,000 tonne biofuel per year						
Relevant Location:	Austria						
Relevant Period:	2001						
Component	Weight (tonnes)	Energy Input (GJ)			Carbon Dioxide Output (tonnes CO2)		
		Average	Range	Percent	Average	Range	Percent
Foundations	2313	2241	272	*2*	95	12	*2*
Structure	715	3504	646	*3*	156	29	*2*
Oilseed Mill Plant	400	91880	22970	*70*	4273	1068	*68*
Biodiesel Processing Plant	158	16205	3200	*12*	816	149	*13*
Storage Facilities	35	12867	5769	*10*	631	284	*10*
Construction Work		4307	0	*3*	316	0	*5*
Total	**3621**	**131004**	**23909**		**6287**	**1116**	

"machinery for the extraction or processing of animal or fixed vegetable oils or fats". Due to the apparent importance of this plant to the total primary energy input and associated CO_2 output, it is recommended that further analysis should be conducted if a more detailed weight breakdown should become available.

3.2.8 Comparison of Results

The results from the energy and carbon analysis of this selection of biomass conversion technologies can be compared and the basis of this is provided in Table 13 which summarises results for power only, heat and power and heat only plants. Table 13 includes the given rating of each plant, measured in terms of the net output of electrical power or heat, as appropriate. In the case of the combined heat and power plant, only the net

Table 13 Comparative Results of Energy and Carbon Analysis for the Manufacture and Construction of Biomass Conversion Plants

Type of Plant	Rating (kW)	Unit Weight (tonnes/kW)	Unit Primary Energy Input (GJ/kW)	Unit Associated CO_2 Output (tonnes/kW)
Power Only – gasification	5500 (e)	2.65	29.1 ± 1.3	1.46 ± 0.06
Power Only – gasification	8000 (e)	0.69	24.7 ± 1.7	1.13 ± 0.09
Power Only – gasification	30000 (e)	0.42	16.9 ± 1.9	0.76 ± 0.09
Power Only – pyrolysis	20000 (e)	1.65	21.1 ± 2.0	0.99 ± 0.09
Heat and Power – gasification	2500 (e)	0.47	23.4 ± 2.8	1.12 ± 0.08
Heat Only – combustion	50 (t)	0.57	14.2 ± 1.6	0.68 ± 0.08
Heat Only – combustion	800 (t)	1.21	7.6 ± 0.6	0.35 ± 0.03

Notes (e) = net electrical output (t) = net thermal output electrical output is specified. Various trends are apparent in the comparative results, in the form of unit weights (tonnes/kW), unit primary energy inputs (GJ/kW) and unit associated CO_2 output (tonnes CO_2/kW). In particular, it would seem that a power rule governs the variation of both the primary energy input and associated CO_2 output of plant manufacture and construction with scale, as represented by plant rating. This is illustrated further in Figures 1 and 2 which summarise energy inputs and CO_2 outputs, respectively. Generally, a similar power rule appears to apply to the results for all types of plant. However, it should be noted that differences between the biomass conversion technologies influence comparative trends in their results. There are obvious differences between the results for the power only, combined heat and power, and heat only plants. Furthermore, there are differences within types of plant, apparent in the results for the wood gasification and wood pyrolysis power only plants. Differences in technology affect the unit weights of the plants, as shown in Table 13. However, the specification of plant components determine the subsequent energy and carbon requirements used in analyses. Consequently, unit primary energy inputs and associated CO_2 outputs do not always reflect patterns in unit weight.

Aside from differences of technology and scale, these results indicate fairly consistent order-of-magnitude values for unit primary energy inputs and associated CO_2 outputs. Such results can be compared with those derived in earlier studies. A preliminary assessment derived estimates of the primary energy inputs and associated CO_2 outputs for the manufacture and construction of a 5 MW(e) wood gasification spark ignition (SI) engine power only plant of **17.3 GJ/kW** and **1.32 tonnes of CO_2/kW**, respectively, and of a 30 MW(e) wood gasification combined cycle gas turbine (CCGT) power only plant of **10.1 GJ/kW** and **0.75 tonnes of CO_2/kW**, respectively (Ref. 2). These are similar order-of-magnitude values to the current results for power only plants. In fact, the unit associated CO_2 outputs for these plants are very similar to those for plants with comparable ratings considered here. In contrast, the unit primary energy inputs from this earlier study are consistently and quite significantly lower that the results from this study. The specific reasons for these differences are probably not simple. For example, the unit weight of **0.43 tonnes/kW** for the 30 MW(e) wood gasification CCGT power only plant is almost exactly the same as the comparable 30 MW(e) wood gasification power only plant evaluated in this study. However, the unit weight of **0.87 tonnes/kW** for the 5 MW(e) wood gasification SI power only plant is substantially less that the 5.5 MW(e) wood gasification power only plant. This may be due to either differences in technology and/or an underestimated weight breakdown in the previous study for this particular plant. Current results can also be contrasted with those included in an initial comparison of primary energy inputs to power plant construction (Ref. 2). In particular, earlier analysis for 8 MW(e) pilot and mature commercial wood gasification CCGT power only plants produced unit primary energy inputs of **119.0 GJ/kW** and **54.4 GJ/kW**, respectively. These values are substantially higher than current results for a similar type and size of plant. These differences are assumed to be due to the use of cost rather than weight data in the analysis. This implies that an unit primary energy input of **52.5 GJ/kW** for a straw burning power only plant (Ref. 3) may also represent an overestimate due to reliance on cost data in the analysis. Finally, unit primary energy inputs of **13.6 ± 2.7 GJ/kW** and **9.8 ± 2.7 GJ/kW** were obtained for a generic 1000 MW(e) conventional coal-fired power only plant and a generic 1000 MW(e) pressurised water reactor nuclear power only plant (Ref. 33). Although similarities might be drawn with current results for wood gasification power only plants, it should be noted that there are significant differences in both technology and scale. Instead, the possibility of translating results between very different technologies is severely constrained. This emphasises the particular importance of current study as a source of definitive results for the manufacture and construction of biomass conversion technologies.

Figure 1 Comparison of Primary Energy Inputs to the Manufacture and Construction of Biomass Conversion Technologies

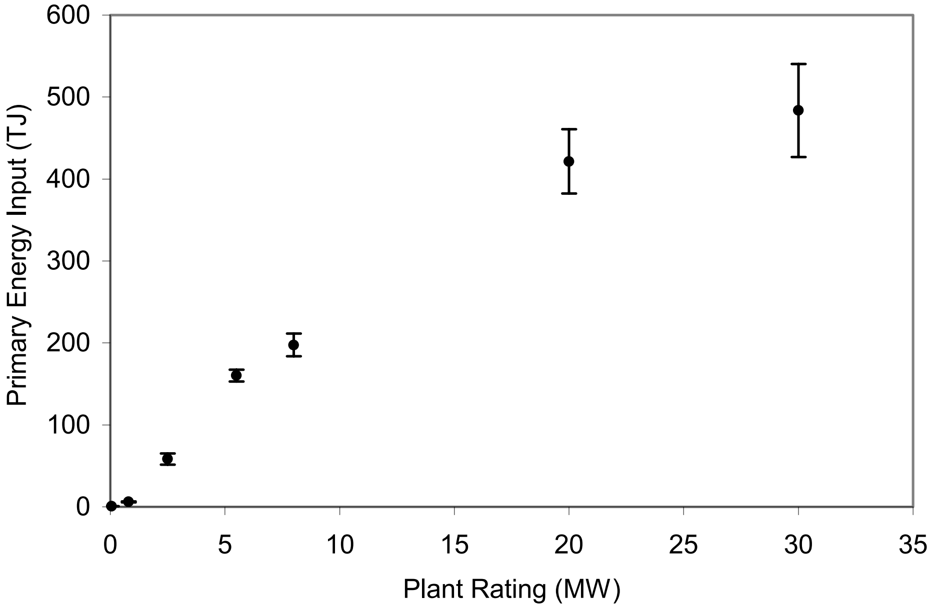
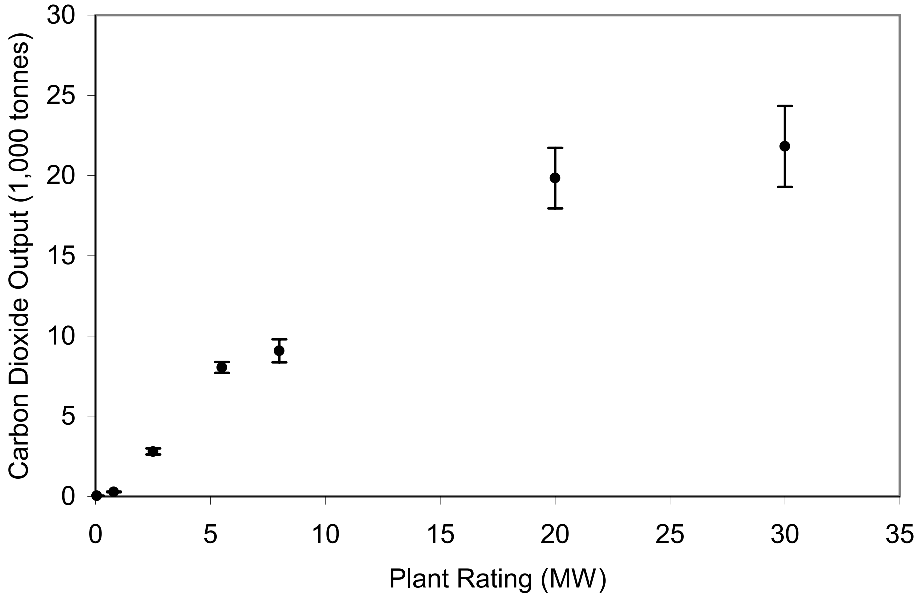


Figure 2 Comparison of Associated CO_2 Outputs from the Manufacture and Construction of Biomass Conversion Technologies



3.3 Start-Up Fuel

Research for a previous study indicated that the use of fossil fuels, such as kerosene or natural gas, as a start-up fuel for biomass conversion technologies may make a substantial contribution to the total primary energy input and the associated CO_2 outputs (Ref. 3). In particular, it was suggested that this may be a significant issue for plants which produce electricity from wood. Hence, attempts were made to determine authoritative start-up fuel consumption rates for such plants in the current study. During site visits, a number of technical manuals were consulted and some of these indicated expected start-up fuel consumption rates for the plants under consideration. However, further discussion with relevant staff revealed that these rates should only be regarded as indicative and highly dependent on the selected start-up regimes and operation conditions. In general, it was felt that such rates could not be taken as authoritative. Instead, it was recommended that realistic start-up fuel consumption rates, and resulting primary energy inputs and associated CO_2 outputs, should only be based on the outcomes of proper commissioning tests. Unfortunately, such tests had not been performed by the time this study had been completed. Hence, it is proposed that existing estimates from the previous study should be adopted until actual data become available.

3.4 Maintenance

During research into the technical details of all the biomass conversion technologies considered here, inquiries were made about actual or proposed maintenance schedules so that estimates of primary energy inputs and associated CO_2 outputs could be determined. In all instances, no data could be provided. For existing plants in operation, only general information on maintenance was available and, for plants under development, it was considered that definitive information would only emerge after a reasonable period of operation had elapsed. Previously, it was assumed that the annual primary energy inputs and associated CO_2 outputs of maintenance could be estimated as **2.5% of the inputs and outputs for plant manufacture and construction** (Ref. 3). Typically, this annual contribution has been taken as between 2.5% and 5% for power plants (see, for example, Refs. 3 and 33). It should also be noted that other studies have assumed a figure of between 5% and 6% for the annual primary energy input of maintenance (Ref. 34). Hence, such approximations seem appropriate. However, it should be noted that these contributions are not relatively minor since they occur annually. Depending on the percentage assumed and the life of the plant, the cumulative contribution of maintenance to the total primary energy input and associated CO_2 output calculated by this method can amount to more that of plant manufacture and construction.

3.5 Decommissioning

The matter of the primary energy inputs and associated CO_2 outputs of plant decommissioning is always a problem for studies such as this due to the general lack of any reliable information. This matter was raised during discussions about the biomass conversion technologies examined here without much success. In most instances, it was stated that this matter could only be resolved in a definitive way when actual decommissioning took place. Since there is little or no experience of this with the types of technology in question, no realistic data were available. However, there has been some limited research into the primary energy inputs and associated CO_2 outputs of building demolition, in general. This has suggested that contributions to primary energy inputs and associated CO_2 outputs arise principally from fuels used by on-site demolition machinery. All other contributions are relatively minor. It has been proposed that net energy and CO_2 might occur due to the recycling of materials from such demolition sites. In particular, the energy and carbon requirements of such secondary materials are usually significantly lower than those of equivalent primary materials. However, it should be noted that the effects of using secondary materials has already been taken into account, implicitly, in the energy and carbon requirements incorporated into the analysis of plant manufacture and construction. Hence, proposed net benefits cannot be assumed in decommissioning since this would constitute double counting. Instead, only the fuel use of the demolition machinery should be evaluated and, based on general information, this results in contributions in the range of **3% to 5% of the primary energy inputs and associated CO_2 outputs** to original plant manufacture and construction.

APPENDIX A: METHODS OF PRESENTING RESULTS

The Excel spreadsheet for presenting results incorporates means to sum both individual rows (for the totals of specific contributions) and columns (for total of inputs/outputs). Simple summation is performed for the “values”, whilst propagation of errors routines are used for the “ranges”. Finally, spaces for the recording of comments are provided in the spreadsheet. These spaces are extremely important since they enable information to be entered on the data and assumptions used in calculations. Such information ensures essential transparency in the recording format and it can be used to qualify results. Additionally, it provides opportunities for other users to modify results, according to their needs and circumstances, in a realistic and systematic manner. The mathematical basis for deriving results assumes that that estimates of primary energy inputs and associated carbon dioxide emissions outputs are likely to be represented by values qualified with ranges rather than just single values in most instances. The ranges will reflect the effects of various factors which cause variations in such estimates. Under these circumstances, the statistical procedures for using the results depend on the nature of the frequency distributions which represent the original data.

In the simplest case, data can be represented by normal or symmetrical frequency distributions. The value and range of the data are based on the mean and the standard deviation, respectively, in the following manner:

Assuming n values of x, then

the mean (value), $m = \frac{1}{n} \Sigma_n x$

and the standard deviation (range), $\sigma = \pm \left\{ \frac{\Sigma_n x^2 - \frac{(\Sigma_n x)^2}{n}}{n - 1} \right\}^{½}$

In some cases, the frequency distribution is non-normal or asymmetrical. Graphically, the data are "skewed" so that the range is not centred about the value. Under these circumstances, the above equations do not apply. However, it is possible to apply them to obtain an approximate value and range by converting the original data using natural logarithms. This effectively transforms the non-normal frequency distribution into an equivalent normal frequency distribution, in the following manner:

If $x' = \log_e x$, then

the mean (value), $m = \exp(m')$

where $m' = \frac{1}{n} \Sigma_n x'$

and the negative standard deviation (lower range),

$\sigma_n = - \{m - \exp(m' - \sigma')\}$

and the positive standard deviation (upper range),

Description of Functional Unit:																							
Unit of Measurement:																							
Relevant Location:																							
Relevant Period:																							
Contribution	Primary Energy Inputs (MJ)												Comments	Carbon Dioxide Outputs (kg CO2)									Comments
	Direct			Indirect			Feedstock			Total				Direct			Indirect			Total			
	Value	Range +	Range -	Value	Range +	Range -	Value	Range +	Range -	Value	Range +	Range -		Value	Range +	Range -	Value	Range +	Range -	Value	Range +	Range -	
		0	0		0	0		0	0	0	0	0								0	0	0	
										0	0	0								0	0	0	
										0	0	0								0	0	0	
										0	0	0								0	0	0	
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										0	0	0								0	0	0	
										0	0	0								0	0	0	
										0	0	0								0	0	0	
Totals	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**		**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	

$$\sigma_p = + \{\exp(m' + \sigma')-m\}$$

$$\text{where } \sigma' = \left\{ \Sigma_n(x')^2 - \frac{(\Sigma_n x')^2}{n} \right\}^{½}$$

Standard propagation of errors routines can be applied to determine the effect on the ranges of different factors on the range of the final result when they are combined. If data are combined together, then the resulting range is derived in the following manner:

If $z = f(x,y)$, then

the standard deviation (range) of z is

$$\sigma_z = \left\{ \left(\frac{\delta z}{\delta x} \sigma_x \right)^2 + \left(\frac{\delta z}{\delta y} \sigma_y \right)^2 \right\}^{½}$$

where σ_x = standard deviation (range) of x

and σ_y = standard deviation (range) of y

If the data are represented by normal or symmetrical frequency distributions, then

the standard deviation (range) of z is

$$\sigma_z = \pm \{ \sigma_x^2 + \sigma_y^2 \}^{½}$$

If the data are represented by non-normal or asymmetrical frequency distributions, then

the negative standard deviation (lower range) of z is

$$\sigma_{zn} = - \{ \sigma_{xn}^2 + \sigma_{yn}^2 \}^{½}$$

where σ_{xn} is the negative standard deviation (lower range) of x
and σ_{yn} is the negative standard deviation (lower range) of y

and the positive standard deviation (upper range) of z is

$$\sigma_{zp} = + \{ \sigma_{xp}^2 + \sigma_{yp}^2 \}^{½}$$

where σ_{xp} is the positive standard deviation (upper range) of x
and σ_{yp} is the positive standard deviation (upper range) of y

APPENDIX B: PROMINENT INPUTS TO BIOMASS SYSTEMS

The initial research which provided the background for evaluating the prominent inputs associated with the carbon and energy modelling of biomass systems was conducted by the Mensuration Branch of the Forestry Authority Research Division of the Forestry Commission (Ref. 1). This work specifically concentrated on the production of biomass from SRC. It did not address the subsequent conversion of wood chips produced from SRC into heat, electricity, etc. Hence, the primary energy inputs and associated carbon dioxide emissions outputs of the construction, maintenance and decommissioning of biomass conversion technologies are excluded from this earlier work. However, related work indicates that biomass production makes a significant contribution to the total energy inputs to and carbon dioxide outputs from biomass conversion systems (for example, Ref. 3). Consequently, the results of this initial work on the carbon and energy analysis of SRC were used to assist the preliminary identification prominent inputs to biomass systems. An example of this preliminary evaluation is presented in Table B1 for wood chip production from a 16 year cycle willow and poplar SRC system (Ref. 1). It can be seen that this indicates that the construction of the storage barn and the fence, and harvesting and chipping operations account for the majority of primary energy inputs (82% of the total primary energy) and associated carbon dioxide emissions outputs (84% to 89% of the total carbon dioxide). It should, however, be noted that, as a specific input, diesel fuel is used in a variety of operations within SRC production which, when combined together, makes a prominent contribution to total primary energy and associated carbon dioxide emissions.

Table B1 Contributions to Primary Energy and Associated Carbon Dioxide Emissions for the Production of SRC Wood Chip (Ref. 1)

Inputs	Contribution to Total Primary Energy (%)	Contribution to Total Carbon Dioxide Emissions (%)
Storage Barn Construction	40	53 - 55
Harvesting and Chipping Operations	30	16 - 18
Fence Construction	12	15 - 16
Other Agricultural Operations	7	2 - 7
Agrochemical Operations	4	4
Wood Chip Transport	4	2
Planting	3	3

Further research has been undertaken on the carbon and energy budgets for the generation of electricity from wood chip produced from forestry wastes and SRC (Ref. 2). This work incorporated preliminary estimates of the primary energy and associated carbon dioxide emissions from power plant construction and maintenance, and the use of start-up fuel in the form of natural gas and kerosene. Hence, results reflect, more appropriately, the total primary energy inputs and associated carbon dioxide emission outputs of complete biomass systems. Moreover, this research is based on the latest views of the production of wood chip from forestry waste and SRC in the United Kingdom. In particular, it is now assumed that wood chip is more likely to be stored and dried at the power plant rather than in separate barns located elsewhere. This alters the pattern of the prominent inputs to the biomass system.

The relative importance of inputs to these biomass systems was determined by evaluating their contributions based on average values of primary energy inputs and associated carbon dioxide emissions outputs. Although the effects on results of sensitivities to certain parameters were investigated in the original source, this was not accounted for here because the computer modelling programme was not available for subsequent use. It is not thought that variations accommodated in the original source significantly alter the conclusions presented here. The results are summarised in Tables B2 to B13. In particular, results for forestry wastes, in the form of forestry thinnings and branchwood, are presented in Tables B2 to B7, whilst those for SRC are given in Tables B8 to B13. Estimated primary energy inputs are shown in Tables B2, B4 and B5 for forestry waste, and Tables B8, B10 and B11 for SRC. Estimated associated carbon dioxide emission outputs are illustrated in Tables B3, B6 and B7 for forestry waste, and Tables B9, B12 and B13 for SRC. Tables B2, B3, B8 and B9 only contain results, ranked in groups of decreasing prominence, for the supply of wood chip from forestry waste and SRC, respectively. Wood chip is assumed to be supplied to a power plant and, hence, the primary energy input and associated carbon dioxide emission outputs for road transport are included in these results. Tables B4 to B7, and B10, to B13 provide results, ranked individually by decreasing prominence, for electricity generation from wood chip-fired power plants. Hence, the primary energy inputs and associated carbon dioxide emission outputs of start-up fuel, construction and maintenance of the power plant are incorporated into these results. It should be noted that inputs to and outputs from power plant decommissioning were not taken into consideration. However, results do reflect the full range of power plant sizes considered in the study, extending from 5 MW(e) to 30 MW(e).

Table B2 indicates that the most important contribution to the primary energy input to wood chip production from forestry waste is diesel fuel (88.6%), with diesel fuel used by the bulk carrier transporting wood chip to the power plant being the largest single component of this (50.6%). The next significant contribution is the manufacture of the bulk carrier (5.2%). The remaining primary energy input (6.2%) mainly derives from the manufacture of the chipper and forwarder (5.4%). The same pattern is apparent in the associated carbon dioxide emission outputs from the production of wood chip from forestry waste, demonstrated in Table B3. The ranking of the contributions is the same but the relative significance of diesel fuel is reduced (75.3%) compared with the results in Table B2. Likewise, the contribution from the diesel fuel for the bulk carrier is decreased (42.9%). However, the importance of contributions from the manufacture of the bulk carrier (11.3%), and the manufacture of the chipper and forwarder (11.9%), which chiefly account for the remaining associated carbon dioxide emission output, are relatively greater.

Table B2 Average Contributions to the Total Primary Energy Input to Wood Chip Production from Forestry Waste (Ref. 2)

Inputs	Contributions to Total Primary Energy Input (%)
Diesel Fuel for:	
Bulk Carrier	50.6
Thinning/Harvesting Forwarder	19.6
Chipper	18.2
Mounder	0.1
Sprayer Forwarder	0.1
Sub-Total for Diesel Fuel	88.6
Manufacture of:	
Bulk Carrier	5.2
Chipper	3.0
Forwarder	2.4
Wire Netting	0.3
Preservative	0.2
Production of Seedlings	0.1
Lubricating Oil for Bulk Carrier	0.1
Miscellaneous	0.1

Table B3 Average Contributions to the Associated Carbon Dioxide Emissions Outputs from Wood Chip Production from Forestry Waste (Ref. 2)

Inputs	Contributions to Associated Carbon Dioxide Emissions Output (%)
Diesel Fuel for:	
Bulk Carrier	42.9
Thinning/Harvesting Forwarder	16.7
Chipper	15.5
Mounder	0.1
Sprayer Forwarder	0.1
Sub-Total for Diesel Fuel	75.3
Manufacture of:	
Bulk Carrier	11.3
Chipper	6.4
Forwarder	5.5
Wire Netting	0.8
Preservative	0.4
Production of Seedlings	0.2
Lubricating Oil for Bulk Carrier	0.1

From Tables B4 and B5, it can be seen that 6 items account for approximately 95% of the total primary energy input to generating electricity from power plants fired by wood chip produced from forestry waste. These items consist of power plant start-up fuel, bulk carrier diesel fuel, power plant construction, thinning/harvesting forwarder diesel fuel, chipper diesel fuel and power plant maintenance. The size of the power plant only influences the order of ranking of the contributions from power plant construction, thinning/harvesting forwarder diesel fuel and chipper diesel fuel. The remaining contribution to total primary energy input (approximately 5%) is chiefly made up of the manufacture of machinery (bulk carrier, forwarder and chipper) and fence components (wire netting and wood preservative). As shown in Tables B6 and B7, similar results are obtained for the contributions to associated carbon dioxide emission outputs from electricity generation with power plants fired by wood chip produced from forestry waste. Approximately 93% of the total associated carbon dioxide emission output is contributed by 7 items, which are the same as those for the total primary energy input plus the manufacture of the bulk carrier. Power plant size has a more marked effect on the ranking order for the contributions from power plant construction, thinning/harvesting forwarder diesel fuel and chipper diesel fuel, and bulk carrier manufacture. The manufacture of forestry machinery (forwarder and chipper) and fence components (wire netting and wood preservative) again make up the majority of the remaining contribution (approximately 7%) of the total associated carbon dioxide emissions.

Table B4 Average Contributions to the Total Primary Energy Input to a 5 MW(e) Power Plant Fired by Wood Chip from Forestry Waste (Ref. 2)

Inputs	Contributions to Total Primary Energy Input (%)
Power Plant Start-up Fuel	40.7
Bulk Carrier Diesel Fuel	22.0
Power Plant Construction	9.8
Thinning/Harvesting Forwarder Diesel Fuel	8.5
Chipper Diesel Fuel	7.9
Power Plant Maintenance	6.1
Bulk Carrier Manufacture	2.3
Chipper Manufacture	1.2
Forwarder Manufacture	1.0
Wire Netting Manufacture	0.1
Preservative Manufacture	0.1
Miscellaneous	0.3

Table B5 Average Contributions to the Total Primary Energy Input to a 30 MW(e) Power Plant Fired by Wood Chip from Forestry Waste (Ref. 2)

Inputs	Contributions to Total Primary Energy Input (%)
Power Plant Start-up Fuel	43.6
Bulk Carrier Diesel Fuel	23.5
Thinning/Harvesting Forwarder Diesel Fuel	9.1
Chipper Diesel Fuel	8.5
Power Plant Construction	6.1
Power Plant Maintenance	3.8
Bulk Carrier Manufacture	2.4
Chipper Manufacture	1.4
Forwarder Manufacture	1.1
Wire Netting Manufacture	0.1
Preservative Manufacture	0.1
Miscellaneous	0.3

Table B6 Average Contributions to the Associated Carbon Dioxide Emissions Outputs from a 5 MW(e) Power Plant Fired by Wood Chip from Forestry Waste (Ref. 2)

Inputs	Contributions to Associated Carbon Dioxide Emissions Output (%)
Power Plant Start-up Fuel	33.7
Bulk Carrier Diesel Fuel	21.1
Power Plant Construction	10.5
Thinning/Harvesting Forwarder Diesel Fuel	8.2
Chipper Diesel Fuel	7.6
Power Plant Maintenance	6.6
Bulk Carrier Manufacture	5.6
Chipper Manufacture	3.1
Forwarder manufacture	2.7
Wire Netting Manufacture	0.4
Preservative Manufacture	0.2
Seedling Production	0.1
Miscellaneous	0.2

Table B7 Average Contributions to the Associated Carbon Dioxide Emissions Outputs from a 30 MW(e) Power Plant Fired by Wood Chip from Forestry Waste (Ref. 2)

Inputs	Contributions to Associated Carbon Dioxide Emissions Output (%)
Power Plant Start-up Fuel	36.4
Bulk Carrier Diesel Fuel	22.8
Thinning/Harvesting Forwarder Diesel Fuel	8.9
Chipper Diesel Fuel	8.2
Power Plant Construction	6.4
Bulk Carrier Manufacture	6.0
Power Plant Maintenance	4.0
Chipper Manufacture	3.4
Forwarder Manufacture	2.9
Wire Netting Manufacture	0.4
Preservative Manufacture	0.2
Mounder Diesel Fuel	0.1
Sprayer Forwarder Diesel Fuel	0.1
Seedling Production	0.1
Straining Wire Manufacture	0.1

There are a larger number of contributions to the total primary energy inputs to the production of wood chip from SRC, as illustrated in Table B8. This shows that the most prominent contribution is diesel fuel (74.0%), of which diesel fuel consumption by the bulk carrier is the single most important factor (36.6%). However, in contrast to the situation for wood chip production from forestry waste, the next most significant contribution comes from the manufacture of wire netting for the SRC plantation fence (7.6%). This is followed by the manufacture of wood preservative used in the fence (4.5%) and then the manufacture of the bulk carrier (3.8%). The remaining contribution to the total primary energy input (10.1%) is comprised of many individual items (22), each of which provides a relatively small contribution (less than 3.8%). This pattern is repeated in terms of associated carbon dioxide emission outputs from the production of wood chip from SRC, as shown in Table B9. The principal contribution is from diesel fuel (55.5%), of which diesel fuel consumption by the bulk carrier is again the most prominent consideration (26.8%). As before, the manufacture of wire netting for the fence (14.9%) is the next in the ranking list, followed by the manufacture of the wood preservative (7.1%), together with the manufacture of the bulk carrier (7.1%). The remaining contribution to the total associated carbon dioxide emission output (15.4%) is composed of 23 items, each with relatively minor individual contributions (less than 4.6%).

Tables B10 and B11 illustrate the ranked contributions of individual items to the total primary energy input to electricity generation from power plants using wood chip from SRC. These show that 6 items account for most of the total primary energy input (approximately 87%). These consist of power plant start-up fuel, bulk carrier diesel fuel, forward harvester diesel fuel, power plant construction, power plant maintenance and wire netting manufacture. The relative ranking of these items is unaffected by the size of the power plant. The remaining contribution (approximately

Table B8 Average Contributions to the Total Primary Energy Input to Wood Chip Production from Short Rotation Coppice (Ref. 2)

Inputs	Contributions to Total Primary Energy Input (%)
Diesel Fuel for:	
Bulk Carrier	36.6
Forward Harvester	26.9
Site Cultivation Tractor	3.8
Planting Tractor	2.2
Transport Loading Tractor	1.9
Rotovating Tractor	1.2
Spraying Tractor	0.8
Harvesting Tractor	0.6
Sub-Total for Diesel Fuel	74.0
Motor Spirit for Brushcutter	1.1
Lubricating Oil for:	
Forward Harvester	0.1
Bulk Carrier	0.1
Manufacture of:	
Wire Netting	7.6
Preservative	4.5
Bulk Carrier	3.8
Forward Harvester	1.8
Glyphosate	1.0
Amitrole	1.0
Straining Wire	0.8
Simazine	0.7
Pendimetholin	0.5
Site Cultivation Tractor	0.3
Planting Tractor	0.3
Transport Loading Tractor	0.3
Metazachlor	0.3
Clopyralid	0.2
Support Post	0.2
Sprayer Tractor	0.1
Harvesting Tractor	0.1
Production of Cuttings	0.9
Beet Up Setts	0.2

Table B9 Average Contributions to the Associated Carbon Dioxide Emissions Outputs from Wood Chip Production from Short Rotation Coppice (Ref. 2)

Inputs	Contributions to Associated Carbon Dioxide Emissions Output (%)
Diesel Fuel for:	
Bulk Carrier	26.8
Forward Harvester	19.6
Site Cultivation Tractor	4.6
Planting Tractor	1.6
Transport Loading Tractor	1.4
Rotovating Tractor	0.6
Harvesting Tractor	0.5
Spraying Tractor	0.4
Sub-Total for Diesel Fuel	55.5
Motor Spirit for Brushcutter	0.8
Manufacture of:	
Wire Netting	14.9
Preservative	7.1
Bulk Carrier	7.1
Forward Harvester	3.3
Straining Wire	1.5
Glyphosate	1.1
Amitrole	1.1
Site Cultivation Tractor	0.8
Simazine	0.7
Planting Tractor	0.6
Transport Loading Tractor	0.5
Pendimetholin	0.5
Harvesting Tractor	0.4
Support Post	0.4
Metazachlor	0.3
Sprayer Tractor	0.2
Transport Loading Trailer	0.2
Clopyralid	0.2
Harvesting Trailer	0.1
Plough	0.1
Planter	0.1
Staples and Nails	0.1
Production of Cuttings	2.0
Beet Up Setts	0.4

Table B10 Average Contributions to the Total Primary Energy Input to a 5 MW(e) Power Plant Fired by Wood Chip from Short Rotation Coppice (Ref. 2)

Inputs	Contributions to Total Primary Energy Input (%)
Power Plant Start-Up Fuel	40.1
Bulk Carrier Diesel Fuel	16.2
Forward Harvester Diesel Fuel	11.9
Power Plant Construction	9.6
Power Plant Maintenance	6.0
Wire Netting Manufacture	3.4
Preservative Manufacture	2.0
Site Cultivation Tractor Diesel Fuel	1.7
Bulk Carrier Manufacture	1.7
Planting Tractor Diesel Fuel	1.0
Transport Tractor Diesel Fuel	0.8
Forward Harvester Manufacture	0.8
Rotovating Tractor Diesel Fuel	0.5
Brushcutter Motor Spirit	0.5
Sprayer Tractor Diesel Fuel	0.4
Glyphosate Manufacture	0.4
Amitrole Manufacture	0.4
Straining Wire Manufacture	0.4
Cuttings Production	0.4
Harvesting Tractor Diesel Fuel	0.3
Simazine Manufacture	0.3
Pendimetholin Manufacture	0.2
Site Cultivation Tractor Manufacture	0.1
Planting Tractor Manufacture	0.1
Transport Loading Tractor Manufacture	0.1
Metazachlor Manufacture	0.1
Clopyralid Manufacture	0.1
Support Post Manufacture	0.1
Beet Up Setts	0.1
Miscellaneous	0.3

Table B11 Average Contributions to the Total Primary Energy Input to a 30 MW(e) Power Plant Fired by Wood Chip from Short Rotation Coppice (Ref. 2)

Inputs	Contributions to Total Primary Energy Input (%)
Power Plant Start-Up Fuel	42.9
Bulk Carrier Diesel Fuel	17.3
Forward Harvester Diesel Fuel	12.7
Power Plant Construction	6.0
Power Plant Maintenance	3.8
Wire Netting Manufacture	3.6
Preservative Manufacture	2.1
Site Cultivation Tractor Diesel Fuel	1.8
Bulk Carrier Manufacture	1.8
Planting Tractor Diesel Fuel	1.0
Transport Tractor Diesel Fuel	0.9
Forward Harvester Manufacture	0.9
Rotovating Tractor Diesel Fuel	0.6
Brushcutter Motor Spirit	0.5
Amitrole Manufacture	0.5
Glyphosate Manufacture	0.5
Spraying Tractor Diesel Fuel	0.4
Straining Wire Manufacture	0.4
Cuttings Production	0.4
Harvesting Tractor Diesel Fuel	0.3
Simazine Manufacture	0.3
Pendimetholin Manufacture	0.2
Site Cultivation Tractor Manufacture	0.1
Planting Tractor Manufacture	0.1
Transport Loading Tractor Manufacture	0.1
Metazachlor Manufacture	0.1
Clopyralid Manufacture	0.1
Support Post Manufacture	0.1
Beet Up Setts	0.1
Miscellaneous	0.4

13%) is made up of 24 different items, mainly consisting of diesel fuel consumed by other machinery (approximately 5%), the manufacture of agricultural machinery and the bulk carrier (approximately 3%), the manufacture of wood preservative (approximately 2%) and agrochemicals (approximately 2%). Similar patterns of relative contribution are found to the total associated carbon dioxide emission outputs from electricity generation from power plants using wood chip from SRC, as shown in Tables B12 and B13. Again, the same 6 items make up the majority of the total associated carbon dioxide emission outputs (approximately 78%). The relative ranking of contributions of these items is the same as that for the total primary energy input, although power plant size affects the order of power plant maintenance and the manufacture of wire netting. The remaining contribution (approximately 22%) is composed of 31 individual items, including the manufacture of agricultural machinery and the bulk carrier (approximately 7%), diesel fuel consumed by other machinery (approximately 5%), the manufacture of wood preservative (approximately 4%) and the manufacture of agrochemicals (approximately 2%).

A number of very important conclusions can be drawn from this assessment of relative contributions to the total primary energy inputs to and total associated carbon dioxide emissions from biomass systems based on forestry waste and SRC. It is clear from the results presented above that the largest single contribution, in terms of both primary energy and associated carbon dioxide emissions, is the power plant start-up fuel. Hence, important factors are the nature of this fuel (kerosene or natural gas), the relevant energy and carbon requirements, and the amounts consumed. The next item in order of prominence is diesel fuel consumed by the bulk carrier and forestry and agricultural machinery, principally the chipper and forwarder. Consequently, the updating of energy and carbon requirements for diesel fuel is a significant consideration. Additional concerns are the fuel consumption rates for these items of equipment, along with the wood chip transport distance and the productivity rates for the chipper and forwarder. Wood chip transport distances are also important parameters in subsequent carbon and energy modelling. More detailed investigation of the primary energy input to and associated carbon dioxide emission output from power plant construction is justified due to their relative prominence. However, it should be noted that a variety of components contribute power plant construction and no one item is likely to dominate. Power plant maintenance is also significant and it is more appropriate to base estimates of primary energy input and associated carbon dioxide emission output on actual materials and activities than nominal percentages, as incorporated in the original work. Remaining items for further possible investigation would seem to be the manufacture of fence components, chiefly wire netting and wood preservative, the manufacture of machinery, such as the bulk carrier, the forwarder and the chipper, and the manufacture of agrochemicals, although these comprise a number of different materials. It should, however, be noted that it has been assumed that no fertiliser is needed in wood chip production from either forestry waste or SRC. There is debate concerning this particular assumption since nutrient depletion may occur in either instance due to the removal of biomass from the cultivation area over a period of time. Hence, it is prudent to update the energy and carbon requirements of fertiliser in case this input is, in fact, found to be necessary in any significant quantities in large-scale applications of these biomass systems.

Table B12 Average Contributions to the Associated Carbon Dioxide Emissions from a 5 MW(e) Power Plant Fired by Wood Chip from Short Rotation Coppice (Ref. 2)

Inputs	Contributions to Associated Carbon Dioxide Emissions (%)
Power Plant Start-Up Fuel	30.6
Bulk Carrier Diesel Fuel	14.4
Forward Harvester Diesel Fuel	10.5
Power Plant Construction	9.6
Wire Netting Manufacture	8.0
Power Plant Maintenance	6.0
Preservative Manufacture	3.8
Bulk Carrier Manufacture	3.8
Site Cultivation Tractor Diesel Fuel	2.5
Forward Harvester Manufacture	1.8
Cutting Production	1.1
Planting Tractor Diesel Fuel	0.9
Transport Loading Tractor Diesel Fuel	0.8
Straining Wire Manufacture	0.8
Glyphosate Manufacture	0.6
Amitrole Manufacture	0.6
Brushcutter Motor Spirit	0.4
Site Cultivation Tractor Manufacture	0.4
Simazine Manufacture	0.4
Rotovating Tractor Diesel Fuel	0.3
Harvesting Tractor Diesel Fuel	0.3
Planting Tractor Manufacture	0.3
Transport Loading Tractor Manufacture	0.3
Pendimetholin Manufacture	0.3
Sprayer Tractor Diesel Fuel	0.2
Harvesting Tractor Manufacture	0.2
Metazachlor Manufacture	0.2
Support Post Manufacture	0.2
Beet Up Setts	0.2
Sprayer Tractor Manufacture	0.1
Harvesting Trailer Manufacture	0.1
Plough and Planter Manufacture	0.1
Transport Loading Trailer	0.1
Clopyralid Manufacture	0.1

Table B13 Average Contributions to the Associated Carbon Dioxide Emissions from a 30 MW(e) Power Plant Fired by Wood Chip from Short Rotation Coppice (Ref. 2)

Inputs	Contributions to Associated Carbon Dioxide Emissions (%)
Power Plant Start-Up Fuel	32.8
Bulk Carrier Diesel Fuel	15.5
Forward Harvester Diesel Fuel	11.3
Wire Netting Manufacture	8.6
Power Plant Construction	5.8
Bulk Carrier Manufacture	4.1
Preservative Manufacture	4.1
Power Plant Maintenance	3.6
Site Cultivation Tractor Diesel Fuel	2.7
Forward Harvester Manufacture	1.9
Cutting Production	1.2
Planting Tractor Diesel Fuel	0.9
Straining Wire Manufacture	0.9
Transport Loading Tractor Diesel Fuel	0.8
Glyphosate Manufacture	0.6
Amitrole Manufacture	0.6
Brushcutter Motor Spirit	0.5
Site Cultivation Tractor Manufacture	0.5
Simazine Manufacture	0.4
Rotovating Tractor Diesel Fuel	0.3
Harvesting Tractor Diesel Fuel	0.3
Planting Tractor Manufacture	0.3
Transport Loading Tractor Manufacture	0.3
Pendimetholin Manufacture	0.3
Sprayer Tractor Diesel Fuel	0.2
Harvesting Tractor Manufacture	0.2
Metazachlor Manufacture	0.2
Support Post Manufacture	0.2
Beet Up Setts	0.2
Sprayer Tractor Manufacture	0.1
Harvesting Trailer Manufacture	0.1
Plough Manufacture	0.1
Planter Manufacture	0.1
Transport Loading Trailer	0.1
Clopyralid Manufacture	0.1
Miscellaneous	0.1

APPENDIX C: ENERGY AND CARBON REQUIREMENTS FROM PROCESS DATA SOURCES

Energy and carbon requirements for prominent inputs to biomass conversion systems have been derived from process data sources and detailed results are presented here. The prominent inputs covered by these results include diesel fuel, road bulk carrier transport, ammonium nitrate fertiliser, rock phosphate fertiliser, super phosphate fertiliser, potash fertiliser, lime, a netting fence, an electric fence, a temporary storage barn and a permanent storage barn. A variety of different data sources have been used. However, in all instances, attempts have been made to ensure that the results are the most recent available and that they are most likely to reflect typical products in the UK. Due to limitations with the original data sources, it has been necessary to simulate UK production using modified data from elsewhere. All major assumptions incorporated in the calculations are explicit.

Table C1 Energy and Carbon Requirements of Diesel Fuel

Specification of the Functional Unit: Diesel fuel delivered to the point of use
Unit of Measurement: kilogram of diesel fuel[(a)]
Relevant Location: United Kingdom
Relevant Period: 1996

Contributions	Primary Energy Inputs (MJ)									Carbon Dioxide Emissions (kg CO_2)						
	Direct		Indirect		Feedstock		Total		Notes	Direct		Indirect		Total		Notes
	Value	Range	Value	Range	Value	Range	Value	Range		Value	Range	Value	Range	Value	Range	
Production			5.02	±0.09			5.02	±0.09	(b)			0.369	±0.005	0.369	±0.005	(c)
Consumption	45.60	±0.20					45.60	±0.20	(d)	3.128	±0.014			3.128	±0.014	(e)
Totals	**45.60**	**±0.20**	**5.02**	**±0.09**			**50.62**	**±0.22**		**3.128**	**±0.014**	**0.369**	**±0.005**	**3.497**	**±0.015**	

Notes

(a) Assuming an average gross calorific value for gas/diesel fuel in the United Kingdom in 1996 of 45.60 ± 0.20 MJ/kg (Refs. C1 and C2) and a density of 1.185 litres/kg for all DERV fuel (Ref. C2).

(b) Assuming the primary energy input to production includes all the primary energy used in extraction, transportation and refining based on a primary energy efficiency of 0.9009 for petroleum products in the United Kingdom in 1996 (Ref. C1).

(c) Assuming the carbon dioxide emissions from production includes all the carbon dioxide released during extraction, transportation and refining based on an upstream carbon dioxide emission factor of 8.093 g CO_2/MJ for road transport fuel in the United Kingdom in 1996 (Ref. C1) and an average gross calorific value for gas/diesel fuel in the United Kingdom in 1996 of 45.60 ± 0.20 MJ/kg (Refs. C1 and C2).

(d) The direct primary energy input of consumption is equal to the energy released when the diesel fuel is combusted and is based on an average gross calorific value for gas/diesel fuel in the United Kingdom in 1996 of 45.60 ± 0.20 MJ/kg (Refs. C1 and C2).

(e) The direct carbon dioxide emission of consumption is equal to the combustion carbon dioxide emission factor of 68.607 g CO_2/MJ (Ref. C1) for the United Kingdom in 1996 and an average gross calorific value for gas/diesel fuel in the United Kingdom in 1996 of 45.60 ± 0.20 MJ/kg (Refs. C1 and C2).

Table C2 Energy and Carbon Requirements of Road Bulk Carrier Transport

Specification of the Functional Unit: Bulk transport with road freight carriers of load capacity between 14.0 and 19.5 tonnes																
Unit of Measurement: tonne-kilometre of load																
Relevant Location: 1994																
Relevant Period: United Kingdom																
Contributions	Primary Energy Inputs (MJ)									Carbon Dioxide Emissions (kg CO_2)						
	Direct		Indirect		Feedstock		Total		Notes	Direct		Indirect		Total		Notes
	Value	Range	Value	Range	Value	Range	Value	Range		Value	Range	Value	Range	Value	Range	
Diesel Fuel	0.8196	±0.0310	0.0902	±0.0034			0.9098	±0.0312	(a)	0.0562	±0.0021	0.0066	±0.0003	0.0628	±0.0021	(b)
Manufacture			0.1920	±0.0350			0.1920	±0.0350	(c)			0.0093	±0.0017	0.0093	±0.0017	(d)
Maintenance			0.0035	±0.0005			0.0035	±0.0005	(e)			0.0002	0	0.0002		(e)
Totals	**0.8196**	**±0.0310**	**0.2857**	**±0.0352**			**1.1053**	**±0.0469**		**0.0562**	**±0.0021**	**0.0161**	**±0.0017**	**0.0723**	**±0.0027**	

Notes

(a) Assuming diesel fuel consumption of between 0.0205 and 0.0221 litres per tonne-kilometre (Ref. C3), an average gross calorific value for diesel fuel in 1996 of 38.48 ± 0.17 MJ/litre (Refs. C1 and C2) and a primary energy efficiency of petroleum production in 1996 of 0.9009 (Ref. C1).

(b) Assuming diesel fuel consumption of between 0.0205 and 0.0221 litres per tonne-kilometre (Ref. C3), a combustion emission factor for diesel fuel in 1996 of 2.640 ± 0.012 kg CO_2/litre (Refs. C1 and C2) and an upstream emission factor for oil and petroleum products of 0.311 ± 0.001 kg CO_2/litre (Ref. C1).

(c) Based on 1994 capital costs and total useful life estimates for road freight transport carriers resulting in an equivalent unit cost of 0.466 to 0.675 pence/tonne-kilometre (Ref. C4) and an energy intensity for "Motor Vehicles and Parts" of 33.6 MJ/£ (Ref. C5).

(d) Based on 1994 capital costs and total useful life estimates for road freight transport carriers resulting in an equivalent unit cost of 0.466 to 0.675 pence/tonne-kilometre (Ref. C4) and a carbon intensity for "Motor Vehicles and Parts" of 1.627 kg CO_2/£ (Ref. C5).

(e) Assuming maintenance and repair costs equal 2% of capital costs (Ref. C6).

Table C3 Energy and Carbon Requirements of Ammonium Nitrate Fertiliser

Specification of the Functional Unit: Bagged ammonium nitrate fertiliser produced via ammonia and nitric acid from natural gas and delivered to the point of use

Unit of Measurement: kilogram of NH_4NO_3 – (1 kg of NH_4NO_3 equals 0.35 kg N)

Relevant Location: United Kingdom

Relevant Period: 1996

Contributions	Primary Energy Inputs (MJ)									Carbon Dioxide Emissions (kg CO_2)						
	Direct		Indirect		Feedstock		Total		Notes	Direct		Indirect		Total		Notes
	Value	Range	Value	Range	Value	Range	Value	Range		Value	Range	Value	Range	Value	Range	
Natural Gas	11.975	±1.950	2.347	±0.956	9.363	±0.376	23.685	±2.204	(a) (b) (c)	0.625	±0.102	0.525	±0.020	1.150	±0.104	(a) (b) (d)
Electricity	0.607	±0.130	1.266	±0.380			1.873	±0.402	(a) (e) (f)			0.091	±0.020	0.091	±0.020	(a) (e) (g)
Capital Plant			1.379	±0.265			1.379	±0.265	(h) (i)			0.067	±0.012			(h) (j)
Packaging			0.354				0.354		(k) (l)			0.005		0.005		(k) (m)
Transport	0.410	±0.016	0.143	±0.018			0.553	±0.024	(n) (o)	0.028	±0.001	0.008	±0.002	0.036	±0.002	(n) (p)
Totals	**12.992**	**±1.954**	**5.489**	**±1.062**	**9.363**	**±0.376**	**27.844**	**±2.256**		**0.653**	**±0.102**	**0.696**	**±0.031**	**1.349**	**±0.107**	

Notes

(a) Based on the requirement of 0.21 kg NH_3/kg NH_4NO_3 and 0.77 kg HNO_3/ NH_4NO_3 for ammonium nitrate production, and the requirement of 0.285 kg NH_3/kg HNO_3 for nitric acid production, resulting in a total requirement of 0.43 kg NH_3/kg NH_4NO_3 (Refs. C7 and C8); natural gas consumption of between 27.0 MJ/ kg NH_3 and 32.6 MJ/kg NH_3 and steam exports of between 0.55 and 6.40 MJ/ kg NH_3 in ammonia production (Ref. C9); steam imports of between 1.352 MJ/ kg HNO_3 and 2.248 MJ/ kg HNO_3 in nitric acid production (Refs. C7 and C10); steam imports of 7.353 MJ/kg NH_4NO_3 in ammonium nitrate production (Ref. C10); and assuming steam raised in natural gas-fired boilers with an 85% efficiency.

(b) Based on natural gas feedstock requirements of between 20.90 MJ/ kg NH_3 and 22.65 MJ/ kg NH_3 for ammonia production (Ref. C9).

(c) Assuming a primary energy efficiency for natural gas production in the United Kingdom in 1996 of 0.9009 (Ref. C1).

(d) Assuming a combustion emission factor of 0.052162 kg CO_2/MJ and an upstream emission factor of 0.001718 kg CO_2/MJ for natural gas in the United Kingdom in 1996 (Ref. C1).

(e) Based on estimated electricity consumption of 0.333 MJ/kg NH_3 and 0.939 MJ/kg NH_3 for ammonia production (Ref. C9); and electricity consumption of 0.334 MJ/kg NH_3 for ammonium nitrate production (Ref. C10).

(f) Assuming a primary energy efficiency for electricity production in the United Kingdom in 1996 of 0.324 (Ref. C1).

(g) Assuming an upstream emission factor of 0.1504 kg CO_2/MJ for electricity in the United Kingdom in 1996 (Ref. C1).

(h) Based on capital cost data for ammonia, nitric acid and ammonium nitrate plants (Refs. C9 and C11).

(i) Based on an energy intensity for "Industrial Plant and Steelwork" of 39 ± 10 MJ/£ (Ref. C5).

(j) Based on a carbon intensity for "Industrial Plant and Steelwork" of 1.9 ± 0.5 kg CO_2/£ (Ref. C5).

(k) Assuming 0.004 kg polyethylene/kg NH_4NO_3.

(l) Based on an energy requirement for polyethylene of 88.55 MJ/kg (Ref. C12).

(m) Based on a carbon requirement for polyethylene of 1.25 kg CO_2/kg (Ref. C12).

(n) Assuming a round trip of 500 km.

(o) Based on a direct energy requirement of 0.820 MJ/t-km and an indirect energy requirement of 0.031 MJ/t-km for road bulk carrier transport.

(p) Based on a direct carbon requirement of 0.056 kg CO_2/t-km and an indirect carbon requirement of 0.016 kg CO_2/t-km for road bulk carrier transport.

Table C4 Energy and Carbon Requirements of Rock Phosphate Fertiliser

Specification of the Functional Unit: Ground, granulated and bagged rock phosphate fertiliser delivered to the point of use																
Unit of Measurement: kilogram of P_2O_5 (rock phosphate containing 32% P_2O_5)																
Relevant Location: United Kingdom																
Relevant Period: 1990																
Contributions	Primary Energy Inputs (MJ)									Carbon Dioxide Emissions (kg CO_2)						
	Direct		Indirect		Feedstock		Total		Notes	Direct		Indirect		Total		Notes
	Value	Range	Value	Range	Value	Range	Value	Range		Value	Range	Value	Range	Value	Range	
Processing	10.200		1.326				11.526		(a) (b)	0.744		0.083		0.827		(a) (c)
Packaging			1.106				1.106		(d) (e)			0.016		0.016		(d) (f)
Shipping	0.625		0.075				0.700		(g) (h)	0.046		0.008		0.054		(g) (i)
Delivery	1.281		0.445				1.726		(j) (k)	0.088		0.025		0.113		(j) (l)
Totals	**12.106**		**2.952**				**15.058**			**0.878**		**0.132**		**1.010**		

Notes

(a) General data assumed to be mainly oil consumption for mining, beneficiation, drying, grinding and granulation (Ref. C13).
(b) Based on an estimated primary energy efficiency of oil production in the United Kingdom in 1990 of 0.885 (Ref. C1).
(c) Based on a combustion emission factor of 0.072987 kg CO_2/MJ and an upstream emission factor of 0.008093 kg CO_2/MJ for oil production in the United Kingdom in 1996 (Ref. C1).
(d) Assuming 0.004 kg polyethylene/kg of phosphate rock containing 32% P_2O_5.
(e) Based on an energy requirement for polyethylene of 88.55 MJ/kg (Ref. C12).
(f) Based on a carbon requirement for polyethylene of 1.25 kg CO_2/kg (Ref. C12).
(g) Assuming a 2000 km round trip by 100,000 t cargo capacity marine bulk carrier from Morocco to the United Kingdom.
(h) Based on a direct energy requirement of 0.100 MJ/t-km and an indirect energy requirement of 0.012 MJ/t-km for 100,000 t cargo capacity marine bulk carrier transport (Ref. C6).
(i) Based on a direct carbon requirement of 0.0073 kg CO_2/t-km and an indirect carbon requirement of 0.0013 kg CO_2/t-km for 100,000 t cargo capacity marine bulk carrier transport.
(j) Assuming a round trip of 500 km by road transport.
(k) Based on a direct energy requirement of 0.820 MJ/t-km and an indirect energy requirement of 0.031 MJ/t-km for road transport.
(l) Based on a direct carbon requirement of 0.056 kg CO_2/t-km and an indirect carbon requirement of 0.016 kg CO_2/t-km for road transport.

Table C5 Energy and Carbon Requirements of Single Superphosphate Fertiliser

Specification of the Functional Unit: Granulated and bagged single superphosphate fertiliser delivered to the point of use
Unit of Measurement: kilogram of P_2O_5 (single superphosphate fertiliser containing 18% P_2O_5)
Relevant Location: United Kingdom
Relevant Period: 1990

Contributions	Primary Energy Inputs (MJ)									Carbon Dioxide Emissions (kg CO_2)						
	Direct		Indirect		Feedstock		Total		Notes	Direct		Indirect		Total		Notes
	Value	Range	Value	Range	Value	Range	Value	Range		Value	Range	Value	Range	Value	Range	
Processing	8.900		1.156				10.056		(a) (b)	0.650		0.072		0.722		(a) (c)
Packaging			1.968				1.968		(d) (e)			0.028		0.028		(d) (f)
Shipping	1.111		0.133				1.244		(g) (h)	0.080		0.013		0.093		(g) (i)
Delivery	2.278		0.792				3.070		(j) (k)	0.156		0.045		0.201		(j) (l)
Totals	**12.289**		**4.049**				**16.338**			**0.886**		**0.158**		**1.044**		

Notes

(a) General data assumed to be mainly oil consumption for mining, grinding, phosphoric and sulphuric acid production, single superphosphate recovery by the hemihydrate wet process, and granulation (Ref. C13).
(b) Based on an estimated primary energy efficiency of oil production in the United Kingdom in 1990 of 0.885 (Ref. C1).
(c) Based on a combustion emission factor of 0.072987 kg CO_2/MJ and an upstream emission factor of 0.008093 kg CO_2/MJ for oil production in the United Kingdom in 1996 (Ref. C1).
(d) Assuming 0.004 kg polyethylene/kg of single superphosphate fertiliser containing 18% P_2O_5.
(e) Based on an energy requirement for polyethylene of 88.55 MJ/kg (Ref. C12).
(f) Based on a carbon requirement for polyethylene of 1.25 kg CO_2/kg (Ref. C12).
(g) Assuming a 2000 km round trip by 100,000 t cargo capacity marine bulk carrier from Morocco to the United Kingdom.
(h) Based on a direct energy requirement of 0.100 MJ/t-km and an indirect energy requirement of 0.012 MJ/t-km for 100,000 t cargo capacity marine bulk carrier transport (Ref. C6).
(i) Based on a direct carbon requirement of 0.0073 kg CO_2/t-km and an indirect carbon requirement of 0.0013 kg CO_2/t-km for 100,000 t cargo capacity marine bulk carrier transport.
(j) Assuming a round trip of 500 km by road bulk carrier.
(k) Based on a direct energy requirement of 0.820 MJ/t-km and an indirect energy requirement of 0.031 MJ/t-km for road bulk carrier transport.
(l) Based on a direct carbon requirement of 0.056 kg CO_2/t-km and an indirect carbon requirement of 0.016 kg CO_2/t-km for road bulk carrier transport.

Table C6 Energy and Carbon Requirements of Triple Superphosphate Fertiliser

Specification of the Functional Unit: Granulated and bagged triple superphosphate fertiliser delivered to the point of use
Unit of Measurement: kilogram of P_2O_5 (triple superphosphate fertiliser containing 46% P_2O_5)
Relevant Location: United Kingdom
Relevant Period: 1990

Contributions	Primary Energy Inputs (MJ)									Carbon Dioxide Emissions (kg CO_2)						
	Direct		Indirect		Feedstock		Total		Notes	Direct		Indirect		Total		Notes
	Value	Range	Value	Range	Value	Range	Value	Range		Value	Range	Value	Range	Value	Range	
Processing	9.900		1.286				11.186		(a) (b)	0.723		0.080		0.803		(a) (c)
Packaging			0.770				0.770		(d) (e)			0.109		0.109		(d) (f)
Shipping	0.435		0.052				0.487		(g) (h)	0.032		0.006		0.038		(g) (i)
Delivery	0.891		0.310				1.201		(j) (k)	0.061		0.017		0.078		(j) (l)
Totals	**11.226**		**2.418**				**13.644**			**0.816**		**0.212**		**1.028**		

Notes

(a) General data assumed to be mainly oil consumption for mining, grinding, phosphoric and sulphuric acid production, triple superphosphate recovery by the hemihydrate wet process, and granulation (Ref. C13).
(b) Based on an estimated primary energy efficiency of oil production in the United Kingdom in 1990 of 0.885 (Ref. C1).
(c) Based on a combustion emission factor of 0.072987 kg CO_2/MJ and an upstream emission factor of 0.008093 kg CO_2/MJ for oil production in the United Kingdom in 1996 (Ref. C1).
(d) Assuming 0.004 kg polyethylene/kg of triple superphosphate fertiliser containing 46% P_2O_5.
(e) Based on an energy requirement for polyethylene of 88.55 MJ/kg (Ref. C12).
(f) Based on a carbon requirement for polyethylene of 1.25 kg CO_2/kg (Ref. C12).
(g) Assuming a 2000 km round trip by 100,000 t cargo capacity marine bulk carrier from Morocco to the United Kingdom.
(h) Based on a direct energy requirement of 0.100 MJ/t-km and an indirect energy requirement of 0.012 MJ/t-km for 100,000 t cargo capacity marine bulk carrier transport (Ref. C6).
(i) Based on a direct carbon requirement of 0.0073 kg CO_2/t-km and an indirect carbon requirement of 0.0013 kg CO_2/t-km for 100,000 t cargo capacity marine bulk carrier transport.
(j) Assuming a round trip of 500 km by road bulk carrier.
(k) Based on a direct energy requirement of 0.820 MJ/t-km and an indirect energy requirement of 0.031 MJ/t-km for road bulk carrier transport.
(l) Based on a direct carbon requirement of 0.056 kg CO_2/t-km and an indirect carbon requirement of 0.016 kg CO_2/t-km for road bulk carrier transport.

Table C7 Energy and Carbon Requirements of Potash Fertiliser

Specification of the Functional Unit: Granulated and bagged potash fertiliser delivered to the point of use																
Unit of Measurement: kilogram of K_2O																
Relevant Location: United Kingdom																
Relevant Period: 1990																
Contributions	Primary Energy Inputs (MJ)									Carbon Dioxide Emissions (kg CO_2)						
	Direct		Indirect		Feedstock		Total		Notes	Direct		Indirect		Total		Notes
	Value	Range	Value	Range	Value	Range	Value	Range		Value	Range	Value	Range	Value	Range	
Processing	6.900		0.897				7.797		(a) (b)	0.504		0.056		0.560		(a) (c)
Packaging			0.354				0.354		(d) (e)			0.005		0.005		(d) (f)
Transport	0.410		0.143				0.553		(g) (h)	0.028		0.008		0.036		(g) (i)
Totals	**7.310**		**1.394**				**8.704**			**0.532**		**0.069**		**0.601**		

Notes

(a) Based on a worldwide average estimate on energy consumption, assumed to mainly consist of oil, for mining, beneficiation, flotation and granulation (Ref. C13).
(b) Based on an estimated primary energy efficiency for oil production in the United Kingdom in 1990 of 0.885 (Ref. C1).
(c) Based on a combustion emission factor of 0.072987 kg CO_2/MJ and an upstream emission factor of 0.008-93 kg CO_2/MJ for oil production in the United Kingdom in 1996 (Ref. C1).
(d) Assuming 0.004 kg polyethylene/kg of K_2O.
(e) Based on an energy requirement for polyethylene of 88.55 MJ/kg (Ref. C12).
(f) Based on a carbon requirement for polyethylene of 1.25 kg CO_2/kg (Ref. C12).
(g) Assuming a round trip of 500 km by road bulk carrier.
(h) Based on a direct energy requirement of 0.8196 MJ/t-km and an indirect energy requirement of 0.2857 MJ/t-km for road transport.
(i) Based on a direct carbon requirement of 0.0562 kg CO_2/t-km and an indirect carbon requirement of 0.0017 kg CO_2/t-km for road transport.

Table C8 Energy and Carbon Requirements of Lime

Specification of the Functional Unit: Ground and bagged lime delivered to the point of use
Unit of Measurement: kilogram of CaO
Relevant Location: United Kingdom
Relevant Period: 1996

Contributions	Primary Energy Inputs (MJ)									Carbon Dioxide Emissions (kg CO_2)						
	Direct		Indirect		Feedstock		Total		Notes	Direct		Indirect		Total		Notes
	Value	Range	Value	Range	Value	Range	Value	Range		Value	Range	Value	Range	Value	Range	
Natural Gas	4.180	±0.190	0.460	±0.092			4.640	±0.211	(a) (b)	0.218	±0.010	0.007		0.225	±0.010	(a) (c)
Electricity	0.220	±0.010	0.459	±0.029			0.679	±0.031	(a) (d)			0.033	±0.002	0.033	±0.002	(a) (e)
Limestone			0.400				0.400		(f) (g)	0.786		0.018		0.804		(f) (h) (i)
Capital Plant			0.020				0.020		(j) (k)			0.001		0.001		(j) (l)
Packaging			0.354				0.354		(m) (n)			0.005		0.005		(m) (o)
Transport	0.246	±0.009	0.086	±0.011			0.332	±0.014	(p) (q)	0.017	±0.001	0.005		0.022	±0.001	(p) (r)
Totals	**4.646**	**±0.190**	**1.779**	**±0.097**			**6.425**	**±0.214**		**1.021**	**±0.010**	**0.069**	**±0.002**	**1.090**	**±0.010**	

Notes

(a) Based on a total direct energy consumption of between 4.2 and 4.6 MJ/kg CaO for rotary kilns in Europe, composed of 95% from natural gas and 5% from electricity (Ref. C14).
(b) Assuming a primary energy efficiency for natural gas production in the United Kingdom in 1996 of 0.9009 (Ref. C1).
(c) Assuming a combustion emission factor of 0.052162 kg CO_2/MJ and an upstream emission factor of 0.001718 kg CO_2/MJ for natural gas in the United Kingdom in 1996 (Ref. C1).
(d) Assuming a primary energy efficiency for electricity production in the United Kingdom in 1996 of 0.324 (Ref. C1).
(e) Assuming an upstream emission factor of 0.1504 kg CO_2/MJ for electricity in the United Kingdom in 1996 (Ref. C1).
(f) Based on a requirement of 2 kg limestone/kg of CaO, including losses due to dust, etc. (Ref. C14).
(g) Assuming an energy requirement of 0.2 MJ/kg of processed limestone for the United Kingdom in 1988 (Ref. C5).
(h) Assuming direct emissions of 0.786 kg CO_2/kg of CaO due to the calcination of limestone.
(i) Assuming a carbon requirement of 0.009 kg CO_2/kg of processed limestone for the United Kingdom in 1988 (Ref. C5).
(j) Based on capital cost data for rotary lime kilns (Ref. C11).
(k) Based on an energy intensity for "Industrial Plant and Steelwork" of 39 ± 10 MJ/£ (Ref. C5).
(l) Based on a carbon intensity for "Industrial Plant and Steelwork" of 1.9 ± 0.5 kg CO_2/£ (Ref. C5).
(m) Assuming 0.004 kg polyethylene/kg CaO.
(n) Based on an energy requirement for polyethylene of 88.55 MJ/kg (Ref. C12).
(o) Based on a carbon requirement for polyethylene of 1.25 kg CO_2/kg (Ref. C12).
(p) Assuming a round trip of 300 km.
(q) Based on a direct energy requirement of 0.8196 ± 0.0310 MJ/t-km and an indirect energy requirement of 0.2857 ± 0.0352 MJ/t-km for road bulk carrier transport.
(r) Based on a direct carbon requirement of 0.0562 ± 0.0021 kg CO_2/t-km and an indirect carbon requirement of 0.0161 ± 0.0017 kg CO_2/t-km for road bulk carrier transport.

Table C9 Energy and Carbon Requirements of Netting Fence

Specification of the Functional Unit: Rabbit/stock fence with steel wire netting and rough softwood stakes, posts and struts

Unit of Measurement: metre length of fence(a)

Relevant Location: United Kingdom

Relevant Period: 1989

Contributions	Primary Energy Inputs (MJ)									Carbon Dioxide Emissions (kg CO_2)						
	Direct		Indirect		Feedstock		Total		Notes	Direct		Indirect		Total		Notes
	Value	Range	Value	Range	Value	Range	Value	Range		Value	Range	Value	Range	Value	Range	
Steel Netting			152.3	±61.3			152.3	±61.3	(b)			7.001	±2.768	7.001	±2.768	(c)
Softwood			0.4	±0.1			0.4	±0.1	(d)			0.031	±0.003	0.031	±0.003	(e)
Preservative			1.2		10.8		12.0		(f)			0.874	±0.004	0.874	±0.004	(g)
Totals			**153.9**	**±61.3**	**10.8**		**164.7**	**±61.3**				**7.906**	**±2.768**	**7.906**	**±2.768**	

Notes

(a) Based on a standard design with 31 mm hexagonal mesh 18 gauge steel wire netting of approximately 1 m exposed height supported by steel wires and rough softwood stakes, straining posts and struts (Ref. C15).

(b) Assuming 1.11 kg of steel netting, wire and staples per m length of fence (Ref. C15) and an energy requirement for steel wire of 137.2 ± 55.2 MJ/kg based on provisional input-output analysis results for 1988 (Refs. C5 and C16).

(c) Assuming 1.11 kg of steel netting, wire and staples per m length of fence (Ref. C15) and a carbon requirement for steel wire of 6.307 ± 2.494 kg CO_2/kg based on provisional input-output analysis results for 1988 (Refs. C5 and C16).

(d) Assuming 0.765 kg of rough softwood per m length of fence (Ref. C15) and an energy requirement of sawlog growing, harvesting and transport of 0.504 ± 0.059 MJ/kg based on forestry data for 2000 (Ref. C17).

(e) Assuming 0.765 kg of rough softwood per m length of fence (Ref. C15) and a carbon requirement of sawlog growing, harvesting and transport of 0.041 ± 0.004 kg CO_2/kg based on forestry data for 2000 (Ref. C17).

(f) Assuming 0.25 kg of wood preservative per m length of fence (Ref. C15) and a gross energy requirement based on non-fuel petroleum products of 48.06 ± 0.11 MJ/kg based on an average gross calorific value of 43.30 ± 0.10 MJ/kg (Ref. C2) and a primary energy efficiency of petroleum production of 0.9009 (Ref. C1).

(g) Assuming 0.25 kg of wood preservative per m length of fence (Ref. C15) and a carbon requirement based on petroleum products of 3.497 ± 0.015 kg CO_2/kg based on a combustion emission factor of 3.128 ± 0.014 kg CO_2/kg and an upstream emission factor for petroleum products of 0.369 ± 0.005 kg CO_2/kg (Ref. C1).

Table C10 Energy and Carbon Requirements of Electric Fence

Specification of the Functional Unit: Stock fence with steel wire and rough softwood stakes, posts and struts
Unit of Measurement: metre length of fence(a)
Relevant Location: United Kingdom
Relevant Period: 1989

Contributions	Primary Energy Inputs (MJ)									Carbon Dioxide Emissions (kg CO_2)						
	Direct		Indirect		Feedstock		Total		Notes	Direct		Indirect		Total		Notes
	Value	Range	Value	Range	Value	Range	Value	Range		Value	Range	Value	Range	Value	Range	
Steel Wire			28.8	±11.6			28.8	±11.6	(b)			1.324	±0.524	1.324	±0.524	(c)
Softwood			0.4	±0.1			0.4	±0.1	(d)			0.031	±0.003	0.031	±0.003	(e)
Preservative			1.2		10.8		12.0		(f)			0.874	±0.004	0.874	±0.004	(g)
Totals			**30.4**	**±11.6**	**10.8**		**41.2**	**±11.6**				**2.229**	**±0.524**	**2.229**	**±0.524**	

Notes

(a) Based on a standard design with single steel wire and rough softwood stakes, straining posts and struts (Ref. C15).

(b) Assuming 0.21 kg of steel wire and staples per m length of fence (Ref. C15) and an energy requirement for steel wire of 137.2 ± 55.2 MJ/kg based on provisional input-output analysis results for 1988 (Refs. C5 and C16).

(c) Assuming 0.21 kg of steel wire and staples per m length of fence (Ref. C15) and a carbon requirement for steel wire of 6.307 ± 2.494 kg CO_2/kg based on provisional input-output analysis results for 1988 (Refs. C5 and C16).

(d) Assuming 0.765 kg of rough softwood per m length of fence (Ref. C15) and an energy requirement of sawlog growing, harvesting and transport of 0.504 ± 0.059 MJ/kg based on forestry data for 2000 (Ref. C17).

(e) Assuming 0.765 kg of rough softwood per m length of fence (Ref. C15) and a carbon requirement of sawlog growing, harvesting and transport of 0.041 ± 0.004 kg CO_2/kg based on forestry data for 2000 (Ref. C17).

(f) Assuming 0.25 kg of wood preservative per m length of fence (Ref. C15) and a gross energy requirement based on non-fuel petroleum products of 48.06 ± 0.11 MJ/kg based on an average gross calorific value of 43.30 ± 0.10 MJ/kg (Ref. C2) and a primary energy efficiency of petroleum production of 0.9009 (Ref. C1).

(g) Assuming 0.25 kg of wood preservative per m length of fence (Ref. C15) and a carbon requirement based on petroleum products of 3.497 ± 0.015 kg CO_2/kg based on a combustion emission factor of 3.128 ± 0.014 kg CO_2/kg and an upstream emission factor for petroleum products of 0.369 ± 0.005 kg CO_2/kg (Ref. C1).

Table C11 Energy and Carbon Requirements of Temporary Storage Barn

Specification of the Functional Unit: Temporary storage barn with timber supports and earth base

Unit of Measurement: 100 tonnes oven dried wood storage capacity$^{(a)}$

Relevant Location: United Kingdom

Relevant Period: 1989

Contributions	Primary Energy Inputs (MJ)									Carbon Dioxide Emissions (kg CO_2)						
	Direct		Indirect		Feedstock		Total		Notes	Direct		Indirect		Total		Notes
	Value	Range	Value	Range	Value	Range	Value	Range		Value	Range	Value	Range	Value	Range	
Construction	13455	±645					13455	±645	(b)	948	±45			948	±45	(c)
Timber			1512	±177			1512	±177	(d)			123	±11	123	±11	(e)
Steel Cladding			368100	±18900			368100	±18900	(f)			16641	±846	16641	±846	(g)
Wire Netting			4116	±1656			4116	±1656	(h)			189	±75	189	±75	(i)
Concrete Blocks			22000				22000		(j)			940		940		(k)
Totals	**13455**	**±645**	**395728**	**±18973**			**409183**	**±18984**		**948**	**±45**	**17893**	**±849**	**18841**	**±851**	

Notes

(a) Based on modifications to a standard design for a temporary barn of an approximate height of 6 m, a floor area of 119 m^2 and a total volume of 715 m^3 which is capable of storing 100 t of oven dried wood with a density of 0.14 t/m^3 at 75% capacity and which has a useful life of approximately 5 years (Ref. C15).

(b) Assuming direct energy input for construction equals 3.4% of the indirect energy input based on the input-output analysis results for 1984 (Ref. C5).

(c) Assuming direct carbon dioxide output from construction equals 5.3% of the indirect carbon dioxide output based on the input-output analysis results for 1984 (Ref. C5).

(d) Based on an estimated 3 t of timber and an energy requirement for rough softwood of 0.504 ± 0.059 MJ/kg based on data for the growing, harvesting and transport of softwood (Ref. C17).

(e) Based on an estimated 3 t of timber and an energy requirement for rough softwood of 0.041 ± 0.004 kg CO_2/kg based on data for the growing, harvesting and transport of softwood (Ref. C17).

(f) Based on an estimated 9 t of steel cladding and an energy requirement for steel sheeting of 40.9 ± 2.1 MJ/kg based on provisional input-output analysis results for 1988.

(g) Based on an estimated 9 t of steel cladding and an energy requirement for steel sheeting of 1.849 ± 0.094 kg CO_2/kg based on provisional input-output analysis results for 1988.

(h) Based on an estimated 30 kg of steel wire netting for the internal wood chip storage space and an energy requirement for wire of 137.2 ± 55.2 MJ/kg based on provisional input-output analysis results for 1988.

(i) Based on an estimated 30 kg of steel wire netting for the internal wood chip storage space and an energy requirement for wire of 6.307 ± 2.494 kg CO_2/kg based on provisional input-output analysis results for 1988.

(j) Based on an estimated 20 t of concrete blocks for the internal wood chip storage space and an energy requirement for concrete of 1.1 MJ/kg based on provisional input-output analysis results for 1988.

(k) Based on an estimated 20 t of concrete blocks for the internal wood chip storage space and an energy requirement for concrete of 0.047 kg CO_2/kg based on provisional input-output analysis results for 1988.

Table C12 Energy and Carbon Requirements of Permanent Storage Barn

Specification of the Functional Unit: Permanent storage barn with structural steel supports and concrete base

Unit of Measurement: 100 tonnes oven dried wood storage capacity[(a)]

Relevant Location: United Kingdom

Relevant Period: 1989

Contributions	Primary Energy Inputs (MJ)									Carbon Dioxide Emissions (kg CO_2)						
	Direct		Indirect		Feedstock		Total		Notes	Direct		Indirect		Total		Notes
	Value	Range	Value	Range	Value	Range	Value	Range		Value	Range	Value	Range	Value	Range	
Construction	25613	±1130					25613	±1130	(b)	1909	±80			1909	±80	(c)
Steelwork			221900	±27300			221900	±27300	(d)			10038	±1239	10038	±1239	(e)
Steel Cladding			368100	±18900			368100	±18900	(f)			16641	±846	16641	±846	(g)
Cement			120000				120000		(h)			7640		7640		(i)
Aggregates			39200				39200		(j)			1520		1520		(k)
Wire Netting			4116	±1656			4116	±1656	(l)			189	±75	189	±75	(m)
Concrete Blocks			22000				22000		(n)			940		940		(o)
Totals	**25613**	**±1130**	**775316**	**±33245**			**800929**	**±33264**		**1909**	**±80**	**36968**	**±1502**	**38877**	**±1504**	

Notes

(a) Based on modifications to a standard design of an approximate height of 6 m, a floor area of 119 m^2 and a total volume of 715 m^3 which is capable of storing 100 t of oven dried wood with a density of 0.14 t/m^3 at 75% capacity and which has a useful life of approximately 25 years (Ref. C15).

(b) Assuming direct energy input for construction equals 3.4% of the indirect energy input based on the input-output analysis results for 1984 (Ref. C5).

(c) Assuming direct carbon dioxide output from construction equals 5.3% of the indirect carbon dioxide output based on the input-output analysis results for 1984 (Ref. C5).

(d) Based on an estimated 7 t of steelwork and an energy requirement for steelwork of 31.7 ± 3.9 MJ/kg based on provisional input-output analysis results for 1988.

(e) Based on an estimated 7 t of steelwork and an energy requirement for steelwork of 1.434 ± 0.177 kg CO_2/kg based on provisional input-output analysis results for 1988.

(f) Based on an estimated 9 t of steel cladding and an energy requirement for steel sheeting of 40.9 ± 2.1 MJ/kg based on provisional input-output analysis results for 1988.

(g) Based on an estimated 9 t of steel cladding and an energy requirement for steel sheeting of 1.849 ± 0.094 kg CO_2/kg based on provisional input-output analysis results for 1988.

(h) Based on an estimated 20 t of cement and an energy requirement for Portland cement of 6.0 MJ/kg based on provisional input-output analysis results for 1988.

(i) Based on an estimated 20 t of cement and an energy requirement for Portland cement of 0.382 kg CO_2/kg based on provisional input-output analysis results for 1988.

(j) Based on an estimated 80 t of aggregates and an energy requirement for cement aggregates of 0.49 MJ/kg based on provisional input-output analysis results for 1988.

(k) Based on an estimated 80 t of aggregates and an energy requirement for cement aggregates of 0.019 kg CO_2/kg based on provisional input-output analysis results for 1988.

(l) Based on an estimated 30 kg of steel wire netting for the internal wood chip storage space and an energy requirement for wire of 137.2 ± 55.2 MJ/kg based on provisional input-output analysis results for 1988.

(m) Based on an estimated 30 kg of steel wire netting for the internal wood chip storage space and an energy requirement for wire of 6.307 ± 2.494 kg CO_2/kg based on provisional input-output analysis results for 1988.

(n) Based on an estimated 20 t of concrete blocks for the internal wood chip storage space and an energy requirement for concrete of 1.1 MJ/kg based on provisional input-output analysis results for 1988.

(o) Based on an estimated 20 t of concrete blocks for the internal wood chip storage space and an energy requirement for concrete of 0.047 kg CO_2/kg based on provisional input-output analysis results for 1988.

REFERENCES FOR APPENDIX C

C1. "Methodology for Environmental Profiles of Construction Materials, Components and Buildings" Centre for Sustainable Construction, Building Research Establishment Ltd., Watford, United Kingdom, 2000.

C2. "Digest of United Kingdom Energy Statistics, 1999" Department of Trade and Industry, The Stationery Office, London, United Kingdom, 1999.

C3. "Production of the Fuel Consumption of Heavy Goods Vehicles by Computer Simulation" by M. Renouf, Transport Road Research Laboratories, United Kingdom, 1979.

C4. Private communication with Prof. M. Browne, Department of Transport Studies, University of Westminster, London, United Kingdom, 4 October 1994.

C5. "An Input-Output Analysis of Carbon Dioxide Emissions for the United Kingdom" by R. Hetherington, Energy Conversion Management, Vol. 37, Nos. 6 – 8, 1996, pp. 979 – 984.

C6. "Handbook of Industrial Energy Analysis" by I. Boustead and G. Hancock, Ellis Horwood Publishers, Chichester, United Kingdom, 1979.

C7. "Ammonium Nitrate" in 'Kirk-Othmer Encyclopedia of Chemical Technology' 4th Edition, Vol. 2, John Wiley and Sons Inc., New York, United States of America, 1992, pp. 698 – 705.

C8. "Nitric Acid" in 'Kirk-Othmer Encyclopedia of Chemical Technology' 4th Edition, Vol. 17, John Wiley and Sons Inc., New York, United States of America, 1996, pp. 80 – 107.

C9. "Modern Production Technologies: Ammonia, Methanol, Hydrogen and Carbon Monoxide" by M. Appl, CRU Publishing Ltd., London, United Kingdom, 1997.

C10. "Energy Expenditures Associated with the Production and Recycle of Metals" by J. C. Bravard, M. B. Flora II and C. Portal, Report ORNL-NSF-EP-24, Oak Ridge National Laboratories, Tennessee, United States of America, 1972.

C11. "Industrial Chemicals" by W. L. Faith, D. B. Keyes and R. L. Clark, John Wiley and Sons Inc., New York, United States of America, 1965.

C12. "Eco-Profiles of the European Plastics Industry, Report 3: Polyethylene and Polypropylene" by I. Boustead, European Centre for Plastics in the Environment, Brussels, Belgium, 1993.

C13. "Energy and Alternatives for Fertilizer and Pesticide Use" by Z. R. Helsel in 'Energy in Farm Production' edited by R. C. Fluck, Energy in World Agriculture, 6, Elsevier, Amsterdam, The Netherlands, 1992.

C14. "Lime and Limestone" in 'Kirk-Othmer Encyclopedia of Chemical Technology' 4th Edition, Vol. 15, John Wiley and Sons Inc., New York, United States of America, 1995. pp. 319 –359.

C15. "Modelling of Carbon and Energy Budgets of Wood Fuel Coppice Systems" by R. W. Matthews, R. L. Robinson, S. R. Abbott and N. Fearis, Report ETSU B/W5/00337/REP, Energy Technology Support Unit, Harwell, United Kingdom, 1994.

C16. "Purchases Inquiry, 1989" Central Statistical Office, Business Monitor PO1008, HMSO, London, United Kingdom, 1989.

C17. "Estimation of Carbon Dioxide and Energy Budgets of Wood-Fired Electricity Generation Systems" by R. W. Matthews and N. D. Mortimer, Report ETSU B/U1/00601/05/REP, Energy Technology Support Unit, Harwell, United Kingdom, 2000.

APPENDIX D: ENERGY AND CARBON REQUIREMENTS FROM STATISTICAL DATA SOURCES

Provisional results from 1988 statistical data sources are given in Tables D1 and D2 deriving energy requirements and carbon requirements, respectively. These results are based on the following relationships:

Linear function $V = AW + B$

Power function $V = A\,W^B$

where V = value of primary energy input (MJ) or carbon dioxide emission output (kg CO_2)
W = weight (kg)
A and B are constants

Both Tables D1 and D2 contain all the relevant information to derive values of average and standard deviations for energy requirements and carbon requirements, respectively. The type of function, either linear or power, which characterises the energy or carbon requirement is specified for each product description. The average values (A.V.) of A and B in the function are summarised, along with the standard deviation (S.D.) of A and B. The average value of the primary energy input or carbon dioxide emission output is found by incorporating the average values of A and B in the appropriate function and inserting the relevant weight of the product under consideration.

Estimated standard deviations for the primary energy input or carbon dioxide emission output for the weight of a given product can be obtained by using the following relationships:

Linear function $\sigma_V = \{[\sigma_A\,W]^2 + [\sigma_B]^2\}^{0.5}$

Power function $\sigma_V = \{[\sigma_A\,W^B)]^2 + [\sigma_B\,A\,W^B\,\log_e(W)]^2\}^{0.5}$

where σ_V = standard deviation of the value of primary energy input (MJ) or carbon dioxide emission output (kg CO_2)
A and B are constants
σ_A = standard deviation of A
σ_B = standard deviation of B
W = weight (kg)

Average values and standard deviations of the subsequent energy and carbon requirements can be obtained by simply dividing the result by the chosen weight of the product. All relevant calculations can be performed using the Excel spreadsheets "Erprod01.xls" and "Coprod01.xls" which have been specifically designed for this purpose.

Table D1 Energy Requirement Information from Statistical Data Sources

Product Description	Function	Energy Requirement Constants			
		A.V. of A	S.D. of A	A.V. of B	S.D. of B
Aluminium, Semi Manufactures	Linear	76.9			
Aluminium, Tubes	Linear	102.8			
Aluminium, Wire	Linear	85.4			
Asphalt, Hot Rolled	Linear	1.2			
Boilers, Firetube	Power	217	24	0.86	0.03
Boilers, Steam < 45 t/hr	Power	346	24	0.83	0.03
Boilers, Steam > 45 t/hr	Power	2446	25	0.61	0.04
Boilers, Auxiliary Plant	Power	705	27	0.82	0.04
Cement, Portland	Linear	6			
Concrete Aggregates	Linear	0.49			
Concrete, Ready Mixed	Linear	1.1			
Conveyors	Power	1948	39	0.64	0.04
Cooling Towers	Power	1927	43	0.75	0.05
Cranes, Overhead Travelling	Power	260	34	0.88	0.02
Electric Conductors, Copper > 1 kV	Linear	69.1	40.9		
Electric Insulators, Ceramic	Linear	82.4	23.1		
Electric Panels > 72.5 kV	Linear	289.8	131		
Fans for Machinery	Power	486	38	0.92	0.03
Furnace Burners	Power	2754	19	0.6	0.03
Furnaces and Ovens, Other	Power	3102	20	0.58	0.03
Gas Turbines < 5 MW	Power	5078	41	0.81	0.06
Gas Turbines 5 MW - 20 MW	Power	176083	50	0.54	0.06
Gas Turbines 20 MW - 50 MW	Power	100353	79	0.57	0.13
Gears and Gearing	Linear	152.1	60.7		
Generating Sets > 750 kVA	Power	437	45	0.92	0.05
Generators, AC > 750 kVA	Power	136	40	0.98	0.05
Granite, Coated Macadam	Linear	1			
Granite, Processed Dry	Linear	0.2			
Heat Exchanger Units	Power	6107	24	0.7	0.03
Hydraulic Power Engines, Other	Power	1043	40	0.82	0.04
Isolating Switches < 72.5 kV	Power	1429	35	0.8	0.04
Isolating Switches > 72.5 kV	Power	8024	34	0.64	0.04
Limestone and Dolomite, Coated	Linear	0.9			
Limestone and Dolomite, Processed	Linear	0.2			
Limestone and Dolomite, Unprocessed	Linear	0.1			
Metal Containers < 100,000 litres	Power	8422	65	0.63	0.05
Metal Containers > 100,000 litres	Power	247	49	0.87	0.04
Mineral Wool, Rock and Slag	Linear	21.2	0.2		
Motors, AC 75 - 375 kW	Power	1184	31	0.65	0.04
Marine Propulsion Engines 1.0 - 2.5 MW	Power	24140	56	0.5	0.09
Marine Propulsion Engines 2.5 - 5.0 MW	Power	312	107	0.9	0.15
Marine Propulsion Engines > 5 MW	Power	8249	36	0.47	0.04
Power Capacitors	Linear	325	20	122734	41776
Prefabricated Structural Components	Linear	2.58	0.32	242161	111949
Pressure Vessels for Chemical Industry	Power	3547	20	0.57	0.02

Table D1 Energy Requirements Information from Statistical Data Sources (contd.)

Product Description	Function	Energy Requirement Constants			
		A.V of A	S.D. of A	A.V. of B	S.D. of B
Pumps, Centrifugal	Power	284	47	0.96	0.05
Pumps, Glandless Impeller	Power	2141	32	0.65	0.03
Pumps, Reciprocating	Power	2924	47	0.73	0.09
Reinforcing Bars, High Tension Steel	Linear	43.3	4.5		
Reinforcing Bars, Mild Steel	Linear	42.9	4.5		
Sand and Gravel, Coated Macadam	Linear	0.98	0.12		
Sand and Gravel	Linear	0.31			
Slag Wool	Linear	62.5	25.7		
Steam Turbines < 10 MW	Power	5500	60	0.69	0.09
Steel Bearing Piles	Linear	36.4	2.6		
Steel Shapes, Welded	Power	523	40	0.65	0.03
Steel Sheet Piling	Linear	40.9	2.1		
Structural Steelwork	Linear	31.7	3.9		
Transformers > 16 kVA	Power	6689	42	0.63	0.06
Transmission Shafts	Power	5276	36	0.51	0.03
Tubes of Alloy Steel	Linear	113.8	23		
Tubes of Cast Iron, Diameter < 152 mm	Linear	62	33.3		
Tubes of Cast Iron, Diameter > 152 mm	Linear	66.6	35.6		
Tubes of Other Alloy Steel	Linear	96.5	10.3		
Tubes of Stainless Steel	Linear	342.4	65.5		
Turbocompressors, Multi-Stage	Power	3158	52	0.77	0.07
Turbogenerators, Driven by Gas Turbines	Power	4905	44	0.77	0.04
Valves, Other	Linear	482.6	135.6		
Valves, Parts	Linear	308.5	29.6		
Wire and Cables, 80 - 100 V	Power	345	40	0.85	0.04

Table D2 Carbon Requirement Information from Statistical Data Sources

Product Description	Function	Carbon Requirement Constants			
		A.V. of A	S.D. of A	A.V. of B	S.D. of B
Aluminium, Semi Manufactures	Linear	3.950			
Aluminium, Tubes	Linear	14.201			
Aluminium, Wire	Linear	11.806			
Asphalt, Hot Rolled	Linear	0.045			
Boilers, Firetube	Power	10.075	1.111	0.86	0.03
Boilers, Steam < 45 t/hr	Power	16.073	1.127	0.83	0.03
Boilers, Steam > 45 t/hr	Power	113.754	1.158	0.61	0.04
Boilers, Auxiliary Plant	Power	32.764	1.266	0.82	0.04
Cement, Portland	Linear	0.382			
Concrete Aggregates	Linear	0.019			
Concrete, Ready Mixed	Linear	0.047			
Conveyors	Power	90.103	1.804	0.64	0.04
Cooling Towers	Power	89.133	1.990	0.75	0.05
Cranes, Overhead Travelling	Power	12.029	1.580	0.88	0.02
Electric Conductors, Copper > 1 kV	Linear	3.894	2.303		
Electric Insulators, Ceramic	Linear	3.008	0.842		
Electric Panels > 72.5 kV	Linear	14.825	6.704		
Fans for Machinery	Power	22.492	1.754	0.92	0.03
Furnace Burners	Power	128.075	0.888	0.6	0.03
Furnaces and Ovens, Other	Power	144.256	0.934	0.58	0.03
Gas Turbines < 5 MW	Power	235.494	1.917	0.81	0.06
Gas Turbines 5 MW - 20 MW	Power	7886.275	2.211	0.54	0.06
Gas Turbines 20 MW - 50 MW	Power	4653.538	3.646	0.57	0.13
Gears and Gearing	Linear	6.710	0.953		
Generating Sets > 750 kVA	Power	20.795	2.128	0.92	0.05
Generators, AC > 750 kVA	Power	6.486	1.913	0.98	0.05
Granite, Coated Macadam	Linear	0.038			
Granite, Processed Dry	Linear	0.009			
Heat Exchanger Units	Power	284.034	1.104	0.7	0.03
Hydraulic Power Engines, Other	Power	48.368	1.841	0.82	0.04
Isolating Switches < 72.5 kV	Power	68.851	1.684	0.8	0.04
Isolating Switches > 72.5 kV	Power	386.570	1.629	0.64	0.04
Limestone and Dolomite, Coated	Linear	0.036			
Limestone and Dolomite, Processed	Linear	0.009			
Limestone and Dolomite, Unprocessed	Linear	0.005			
Metal Containers < 100,000 litres	Power	414.034	3.198	0.63	0.05
Metal Containers > 100,000 litres	Power	12.142	2.422	0.87	0.04
Mineral Wool, Rock and Slag	Linear	1.065	0.009		
Motors, AC 75 - 375 kW	Power	57.051	1.474	0.65	0.04
Marine Propulsion Engines 1.0 - 2.5 MW	Power	1119.419	2.613	0.5	0.09
Marine Propulsion Engines 2.5 - 5.0 MW	Power	14.460	4.940	0.9	0.15
Marine Propulsion Engines > 5 MW	Power	382.526	1.668	0.47	0.04
Power Capacitors	Linear	15.474	0.962	5837.588	1986.977
Prefabricated Structural Components	Linear	0.127	0.016	11904.983	5503.584
Pressure Vessels for Chemical Industry	Power	164.976	0.911	0.57	0.02

Table D2 Carbon Requirement Information from Statistical Data Sources (contd.)

Product Description	Function	Carbon Requirement Constants			
		Mean of A	S.D. of A	Mean of B	S.D. of B
Pumps, Centrifugal	Power	13.124	2.152	0.96	0.05
Pumps, Glandless Impeller	Power	99.022	1.493	0.65	0.03
Pumps, Reciprocating	Power	135.223	2.165	0.73	0.09
Reinforcing Bars, High Tension Steel	Linear	1.959	0.203		
Reinforcing Bars, Mild Steel	Linear	1.938	0.203		
Sand and Gravel, Coated Macadam	Linear	0.038	0.005		
Sand and Gravel	Linear	0.012			
Slag Wool	Linear	2.414	0.994		
Steam Turbines < 10 MW	Power	255.067	2.750	0.69	0.09
Steel Bearing Piles	Linear	1.647	0.119		
Steel Shapes, Welded	Power	25.708	1.947	0.65	0.03
Steel Sheet Piling	Linear	1.849	0.094		
Structural Steelwork	Linear	1.434	0.177		
Transformers > 16 kVA	Power	318.137	1.981	0.63	0.06
Transmission Shafts	Power	232.716	1.584	0.51	0.03
Tubes of Alloy Steel	Linear	5.143	1.039		
Tubes of Cast Iron, Diameter < 152 mm	Linear	2.805	1.507		
Tubes of Cast Iron, Diameter > 152 mm	Linear	3.013	1.610		
Tubes of Other Alloy Steel	Linear	4.364	0.468		
Tubes of Stainless Steel	Linear	15.481	2.961		
Turbocompressors, Multi-Stage	Power	146.423	2.427	0.77	0.07
Turbogenerators, Driven by Gas Turbines	Power	227.455	2.053	0.77	0.04
Valves, Other	Linear	22.317	6.270		
Valves, Parts	Linear	14.269	1.368		
Wire and Cables, 80 - 100 V	Power	19.370	2.270	0.85	0.04

APPENDIX E: REVIEW OF EXISTING STUDIES

In the early stages of this project, 16 sources were identified which might contain information relevant to the carbon and energy analysis of biomass systems. Attempts were made to obtain copies of all these reports and, where necessary, supplementary material and further details. In some instances, there have been delays in obtaining the relevant reports and, hence, only preliminary reviews were possible, based on information provided in the initial sources, such as published and website abstracts. Where full details were available, subsequent reviews are brief and concentrate on information directly relevant to the current project, especially concerning the primary energy inputs and associated carbon dioxide emission outputs for the construction, maintenance and decommissioning of biomass conversion technologies. However, other specific information, such as energy and carbon requirements, for diesel fuel, fertiliser and bulk materials were also considered to be of interest. Additionally, it was considered helpful to note results, in the form of primary energy inputs and associated carbon dioxide emission outputs, for a range of biomass systems for subsequent comparison.

Brief reviews of existing, relatively recent, research studies, from the mid-1990’s, are presented in the date order of publication of the main references below. Comparative results for the gross energy requirements and carbon requirements of diesel fuel and biodiesel are summarised in Tables E1 and E2, respectively. These indicate that similar bases of calculation were probably used in the two relevant studies, although there may be some inconsistency over the interpretation of primary energy as non-renewable energy. Unfortunately, the results presented in these studies only enabled direct comparison of the gross energy requirement of diesel fuel and a significant discrepancy is apparent in the results presented. Inadequate details were available in the published references to explain this discrepancy.

Tables E3 and E4 summarise the basic assumptions incorporated into the studies which estimated the energy inputs and/or associated carbon dioxide emissions from conventional and biomass power plants, respectively. Each study appeared to use primary energy as a basis for calculating energy inputs to either type of power plant, although there was uncertainty in many cases over whether this was interpreted as non-renewable energy. All studies, except one, definitely accounted for power plant construction in the calculation of total energy inputs. Considerably mixed experience with the evaluation of energy inputs to power plant maintenance and decommissioning was encountered. No study definitely accounted for start-up fuel in the estimation of energy inputs and associated carbon dioxide emissions with biomass power plants. Comparison of specific results from different studies was not possible due to the ways in which these were calculated and presented. It was concluded that further investigation of the studies, probably using detailed information directly from the authors, would be needed to achieve meaningful quantitative comparison and any explanation of subsequent similarities and differences.

Table E1 Comparative Results for Diesel Fuel

Source	Basis of Calculation		Gross Energy Requirement		Carbon Requirement
Author and Year	Primary Energy	Non-Renewable Energy	(MJ/MJ)	(MJ/kg)	(kg CO_2/kg)
Kaltschmitt et al, 1997	✓	?	?	41.20	3.08
Sheehan et al, 1998	✓	✓	1.995	54.94	?

Table E2 Comparative Results for Biodiesel

Source	Basis of Calculation		Gross Energy Requirement		Carbon Requirement
Author and Year	Primary Energy	Non-Renewable Energy	(MJ/MJ)	(MJ/kg)	(kg CO_2/kg)
Kaltschmitt et al, 1997	✓	?	?	14.20	0.92
Sheehan et al, 1998	✓	✓	0.311	?	?

Table E3 Basic Assumptions for Conventional Power Plants

Source	Basis of Calculation		Life Cycle Components		
Author and Year	Primary Energy	Non-Renewable Energy	Construction	Maintenance	Decommissioning
Dubuisson and Sintzoff, 1998	✓	?	✓	X	X
Hartmann and Kaltschmidt, 1999	✓	?	✓	?	✓
Spath at al, 1999	✓	?	✓	✓	✓

Table E4 Basic Assumptions for Biomass Power Plants

Source	Type of Power Plant	Basis of Calculations		Life Cycle Components			
Author and Year		Primary Energy	Non-Renewable Energy	Construction	Start-Up Fuel	Maintenance	Decommissioning
Mann and Spath, 1997	Biomass Gasification Combined Cycle Power Only Plant	✓	✓	✓	X	?	✓
Dubuisson and Sintzoff, 1998	Biomass Gasification and Diesel Gas Engine Power Only Plant	✓	?	✓	?	X	X
Dubuisson and Sintzoff, 1998	Biomass Gasification Gas Engine Combined Heat and Power Plant	✓	?	✓	?	X	X
Dubuisson and Sintzoff, 1998	Biomass and Coal Power Only Plant	✓	?	✓	?	X	X
Jungmeier et al, 1998	Biomass Combined Heat and Power Plant	✓	✓	✓	?	?	✓
Baguant and Beeharry, 1998	Biomass Power Only Plant	✓	✓	?	?	?	?
Hartmann and Kaltschmidt, 1999	Biomass and Coal Power Only Plant	✓	✓	✓	?	?	✓

“Methanol and Hydrogen from Biomass for Transportation with Comparisons to Methanol and Hydrogen from Natural Gas and Coal”
by R. H. Williams et al,
US Environmental Protection Agency,
EPA-600/R-96-072,
Published in the Proceedings of the 1995 Symposium on Greenhouse Gas Emissions and Mitigation Research,
1996.

A brief summary in Fuel and Energy Abstracts, May 1997, suggests that carbon dioxide emissions have been calculated for the production of methanol and hydrogen, as transport fuels, from biomass. No specific results are quoted.

“Life Cycle Analysis of Selected Biomass and Fossil Fuel Energy Systems in Denmark and Ghana - with focus on greenhouse gas emissions”
by P. S. Neilsen,
Report R-036, PhD Thesis,
Department of Buildings and Energy, Technical University of Denmark, Denmark,
1996.

In addition to the full text in the PhD thesis, brief summary is available via website: www.ibe.dtu.dk/publikationer/rapport/psr. The study consists of life cycle analyses, which specifically concentrate on greenhouse gas emissions, for a variety of energy technologies in Denmark and Ghana. In particular, the study examines combined heat and power generation from wood chips and straw in Denmark, and electricity production from wood in Ghana. Comparative studies of combined heat and power generation from natural gas and biogas in Denmark, and electricity generation from oil in Ghana are included. Based on the findings of another study ("Livsforløbsanalyser af Decentrale Kraftvarmeværker - energi og miljø-analyse" by P. B. Petersen, Technical University of Denmark, Denmark, 1991), which is only available in Danish, the energy consumption of power plant construction and decommissioning are considered to be negligible, whereas the energy consumption of operation and maintenance are assumed to comprise of 5% - 6% of the energy output of the power plant. The energy input and associated carbon dioxide output of start-up fuel do not seem to be taken into account.

“Life-Cycle Analysis of Energy Systems”
by B. Kuemmel, S. K. Nielsen and B. Sorensen,
Roskilde University, Denmark,
1997.

A book review in Applied Energy, Vol. 59, Nos. 2 - 3, 1998, indicates that examples of the results of life cycle analysis studies of “electric power production by various sources of energy” are presented. A copy of this book could not be obtained.

“Life Cycle Analysis of Biofuels under Different Environmental Aspects”
by M. Kaltschmitt, G. A. Reinhard and T. Stelzer,
Institut für Energiewirtschaft und Rationelle Energieanwendung (IER; Institute of Energy, Economics and the Rational Use of Energy), University of Stuttgart, Germany, and Institut für Energie- und Umweltforschung (IFEU) Heidelburg GmbH, Germany,
Published in Biomass and Bioenergy, Vol. 12, No. 2, pp. 121 - 134,
1997.

This life cycle analysis study compares various environmental impacts, including primary energy resource depletion and global warming potential, of producing diesel oil and rapeseed methyl ester (RME). It is not clear whether primary energy refers to non-renewable resources, but separate data on the carbon dioxide emissions from the combustion of fossil fuels are given. The calculations for RME production appear to cover all activities and inputs, including nitrogen, phosphorus, potassium and calcium fertilisers. However, specific details are not presented and the original source of such data is not immediately apparent. Conversion of results suggests energy requirements of 41.2 MJ/kg for diesel fuel and of 14.2 MJ/kg for RME. The carbon requirements for diesel fuel are 3.08 kg CO_2*/kg and for RME are 0.91 kg* CO_2*/kg. Comparisons with other biofuels and biomass energy are provided but these are presented graphically and relevant details are not given.*

"Towards a Standard Methodology for Greenhouse Gas Balances of Bioenergy Systems in Comparison with Fossil Energy Systems"
by B. Schlamadinger, M. Apps, F. Bohlin, L. Gustavsson, G. Jungmeier, G. Marland, K. Pingoud and I. Savolainen,
Joanneum Research, Graz, Austria, Department of Natural Resources Canada, Edmonton, Canada, Department of Forestry-Industry-Market Studies, Swedish University of Agricultural Science, Uppsala, Sweden, Department of Environmental and Energy System Studies, Lund University, Sweden, Oak Ridge National Laboratory, Oak Ridge, USA, and Technical Research Centre of Finland, Espoo, Finland.
Published in Biomass and Bioenergy, Vol. 13, No. 6, pp. 359 -375,
1997

The stated purpose of this study is not to produce new results. Instead, it reviews existing work and examines the basis for common comparison between results derived from different sources and by different methods. However, the comparison presented is qualitative rather than quantitative, probably due to difficulties in determining the details of the basis for calculation used in the quoted work. It is indicated that energy and carbon dioxide emissions are a key feature in many studies. Additionally, it is noted that some studies evaluate energy inputs and associated carbon dioxide outputs from power plant construction. There are references to various studies which have been conducted since 1990.

"Life-Cycle Analysis of a Fossil-Fuel Power Plant with CO_2 and a Sequestering System"
by M. Akai, N. Nomura, H. Waku and M. Inoue,
Mechanical Engineering Laboratory, MITI, Institute of Applied Energy and New Energy and Industrial Technology Development Organisation, Japan,
Published in Energy, Vol. 22, Nos. 2/3, pp. 249 - 255,
1997.

This paper presents the results of a life cycle analysis study which compares the net primary energy input and emissions outputs (CO_2*,* NO_x*, and* SO_x*) of various fossil fuel-fired power plants incorporating carbon dioxide sequestration systems with conventional power plants. The results include the primary energy inputs and carbon dioxide emissions outputs of power plant construction and miscellaneous operation and maintenance, but not decommissioning. Unfortunately, the results are presented graphically and it is not possible to decipher specific contributions in the paper. It would appear that relevant details may be available from the original source, in Japanese, which is "Energy Analysis on Power Generation Plants" by Y. Uchiyama and H. Yamamoto, Report Y90015, Central Research Institute of Electricity, Tokyo, Japan, 1991.*

“Life Cycle Assessment of a Biomass Gasification Combined-Cycle System”
by M. K. Mann and P. L. Spath,
NREL/TP-430-23076,
National Renewable Energy Laboratory, Golden, Colorado, United States of America,
December 1997.

This is a very detailed report of a life cycle analysis study of electricity generation from an integrated gasification combined cycle (gas and steam turbines) power plant, with a net capacity of 113 MW(e), which uses wood chip produced from short rotation coppice. The life cycle analysis study concentrates on the estimation of primary energy as a means of evaluating non-renewable energy resource depletion, and emissions to air, including carbon dioxide from all sources. The report contains information on sources of energy and carbon requirements for fertilisers and herbicides. Additionally, there is a list of 11 related studies, conducted between 1981 and 1996, along with brief reviews. Although the report is extensive, details of calculation are obscured by the way in which results are presented. In particular, power plant construction and decommissioning is covered by the report but estimates of primary energy inputs and associated carbon dioxide emissions outputs are not presented. It would appear that such results are generated for power plant construction using a weight breakdown for bulk materials; concrete, steel, aluminium and iron. It is not clear whether the energy and associated carbon dioxide emission for processing and assembling these materials, manufacturing power plant machinery and equipment, etc., have been taken into account. The assumptions concerning power plant decommissioning are not stated. It would appear that the effects of start-up fuel are not incorporated into this life cycle analysis.

“Electricity from a Competitive Market in Life-Cycle Analysis”
by. T. Kåberger and R. Karlsson,
Institute of Physical Resource Theory, and Systems Management, Chalmers University of Technology, Gothenburg, Sweden,
Published in Journal of Cleaner Production, Vol. 6, pp. 103 - 109,
1998.

This general paper addresses methodology and does not present specific results. However, it suggests possible other sources of relevant results, chiefly “Energy Issues in Life-Cycle Assessment” by Virtanen, Meiettinen and Juntilla (editors), UETP-EEE, Helsinki, Finland, 1995, and “Oekobalanz von Packstoffen Stand 1990” by K. Habersatter, Shriftenreihe Umwelt No. 132, BUWAL, Bern, Switzerland, 1990.

“Energy and CO_2 Balances in Different Power Generation Routes using Wood Fuel from Short Rotation Coppice”
by X. Dubuisson and I. Sintzoff,
Université Catholique Louvain, Louvain-la-Neuve, Belgium,
Published in Biomass and Bioenergy, Vol. 15, Nos. 4/5, pp. 379 - 390,
1998.

This study evaluates and compares the primary energy inputs and associated carbon dioxide emission outputs of energy production using wood chips derived from short rotation coppice. The wood chips are used in three different types of system; a gasification and gas engine power plant for local peak electricity generation, a gasification and gas engine combined heat and power (CHP) plant for local electricity and district heat cogeneration, and a centralised power plant with wood and coal co-firing. The primary energy input for power plant construction is given as 3,000 to 6,000 MJ/MW(e) installed. However, the relative sizes/capacities of these systems is *not specified in the paper. Power plant maintenance and decommissioning have not been taken into account. Results are presented for the energy and carbon requirements of generating output (electricity only, or heat and electricity) from the options considered but some details are obscure and terms are not clearly defined. However, the relevant energy requirements appear to be 0.0400 ± 0.0016 MJ/MJ(e) for the peaking gas engine, 0.0164 ± 0.0003 MJ/MJ(heat and power) for the CHP plant, and 0.0303 ± 0.0009 MJ/MJ(e) for the co-fired power plant. The carbon requirements are 0.026 ± 0.002 kg CO_2/MJ(e) for the peaking gas engine, 0.011 ± 0.001 kg CO_2/MJ(heat and power) for the CHP plant and 0.044 ± 0.001 kg CO_2/MJ(e) for the co-fired power plant. Reference data are provided for a conventional alternatives, including a coal-fired power plant which give a carbon requirement of 0.161 ± 0.018 kg CO_2/MJ(e). The source of this information appears to be the ExternE project which was funded by Directorate-General RESEARCH (formerly XII) of the European Commission. The original source of results for the wood-fired power plants is not immediately apparent.*

"Environmental Burdens over the Entire Life Cycle of a Biomass CHP Plant"
by G. Jungmeier, G. Resch and J. Spitzer,
Joanneum Research, Graz, Austria,
Published in Biomass and Bioenergy, Vol. 15, Nos. 4/5, pp. 311 - 323,
1998.

This study was conducted as a part of the ExternE project which was funded by Directorate-General RESEARCH (formerly XII) of the European Commission. The power plant examined consists of a combined heat and power plant (CHP), with outputs of 1.265 MW(e) and 6.300 MW(t), located at Reuthe in Austria. The power plant burns wood waste, in the form of wood powder, sawdust and shavings, and wood chips from forestry residues. Conventional wood burning, with a moving grate burner and muffle burner, is used. The study appears to mainly concentrate on emissions. In particular, the carbon dioxide emission from power plant construction, operation and dismantling are calculated. Only the carbon dioxide emissions associated with power plant construction are quoted in the paper. These amount to a total of 6,900 tonnes of carbon dioxide, giving an equivalent of 5,455 tonnes CO_2/MW(e) installed. It would seem that further details may be available in a dissertation entitled "Life Cycle Inventory of a Biomass Fired Combined Heat and Power Plant" by G. Resch, Vol. 80, Technical University of Graz, Austria, 1997.

"Life-Cycle Assessment of Sugar Cane Bio-Energy Systems for Electricity Production"
by J. Baguant and R. P. Beeharry,
Department of Chemical and Sugar Engineering, Faculty of Engineering, University of Mauritius, Mauritius,
January 1998.

A brief summary of this study is available on website: www.prosi.net/mag98. The summary reports a life cycle analysis study which has been conducted to evaluate the total environmental and resource utilisation impact of using sugar cane tops, leaves and trash to generate electricity. The study appears to concentrate on the estimation of net energy (presumably primary energy from fossil fuels excluding the energy in the sugar cane biomass) and carbon dioxide emissions. It seems unlikely that the primary energy inputs and associated carbon dioxide emission outputs of power plant construction, maintenance and decommissioning have been taken into account. On this basis, the primary energy requirement of electricity generated from sugar cane biomass is 0.11 to 0.28 MJ/MJ(e). Avoided carbon dioxide emissions are *also quoted rather than the total associated carbon dioxide emissions output. Such information and further details of the study may be in the original copy of the report.*

"Life Cycle Inventories of Biodiesel and Petroleum Diesel for Use in an Urban Bus"

by J. Sheehan, V. Camobreco, J. Duffield, M. Graboski and H. Shapouri,
NREL/SR-580-24089,
National Renewable Energy Laboratory, Golden, Colorado, United States of America,
May 1998

This report provides an extremely detailed summary of a life cycle analysis study which compares biodiesel produced from soyabeans with diesel fuel available in the United States of America. Results are presented in different forms including energy requirements measured in terms of fossil fuel consumption which is generally equivalent to primary energy use considered in this project. On this basis, the energy requirement of biodiesel is 0.3111 MJ/MJ of energy in the fuel. The energy requirement of diesel fuel is 1.1995 MJ /MJ of energy in the fuel. Assuming a gross calorific value of 45.8 MJ/kg of diesel fuel, this would result in a gross energy requirement of 54.94 MJ/kg (cf. estimates quoted in Section 2.4.1). Carbon requirements are quoted in terms of carbon dioxide emitted from fossil fuel combustion per brake horsepower - hour (bhp-h) produced by burning fuel in an urban bus. On this basis, the carbon requirement of biodiesel is 0.136 kg CO_2*/bhp-h, and for diesel fuel is 0.633 kg* CO_2*/bhp-h. In addition, useful supplementary information is included in the report, including energy and carbon requirements for nitrogen, phosphate and potash fertilisers.*

"Electricity Generation from Solid Biomass via Co-combustion with Coal: Energy and Emission Balances from a German Case Study"
by. D. Hartmann and M. Kaltschmidt,
Institut für Energiewirtschaft und Rationelle Energieanwendung (IER; Institute of Energy, Economics and the Rational Use of Energy), University of Stuttgart, Germany,
Published in Biomass and Bioenergy, Vol. 16, pp. 397 - 406,
1999.

This life cycle analysis study compares the primary energy inputs and emissions, including carbon dioxide, of a power plant with flue gas desulphurisation burning hard coal, and mixtures of hard coal and biomass, consisting of straw or wood from forest residues. It is stated that the primary energy and carbon dioxide emissions associated with power plant construction and demolition are included in the calculations although the data are not given explicitly. There are indications that these data are contained in other references, most probably a dissertation in German, entitled "Solid Biomass as a Substitute for Fossil Energy Carrier - Energy and Emission Balances" by S. Becher, Faculty for Energy Technology, University of Stuttgart, July 1997. The specifications of the power plants presented in the paper are ambiguous, as the ratio of hard coal to biomass for co-combustion seem to have been transposed. Energy requirements (measured in non-renewable primary energy per unit of electricity) and carbon requirements (measured in carbon dioxide per unit of electricity) are presented; 2.54 MJ/MJ(e) and 0.230 kg CO_2*/MJ(e) for a power plant burning hard coal only; 0.13 MJ/MJ(e) and 0.006 kg* CO_2*/MJ(e) for a power plant burning hard coal and straw: 0.12 MJ/MJ(e) and 0.006 kg* CO_2*/MJ(e) for a power plant burning hard coal and wood from forest residue.*

"Life Cycle Assessment of Coal-Fired Power Production"

by P. L. Spath, M. K. Mann and D. R. Kerr,
NREL/TP-570-25119,
National Renewable Energy Laboratory, Golden, Colorado, United States of America,
June 1999.

Although this study does not cover energy production from biomass conversion systems, it was thought to be relevant for reference results for conventional electricity generation. The report summarises a life cycle analysis study of electricity generation from three different types of coal-fired power plant; an average pulverised coal-fired power plant (360 MW net electrical capacity) in the United States of America in 1995 based on conventional technology with flue gas desulphurisation, a modern coal-fired power plant (425 MW net electrical capacity) with flue gas cleaning systems which meet the New Source Performance Standards, and a future coal-fired power plant (404 MW net electrical capacity) incorporating a Low Emission Boiler System. Although the study concentrates on emissions to air, including carbon dioxide, primary energy inputs are also estimated. It appears that estimates of primary energy inputs and associated carbon dioxide emissions outputs for power plant construction are based weight breakdowns of bulk material; concrete, steel, aluminium and iron. Unfortunately, the details of calculations and subsequent results are not available in a suitable format. The reason for this may be that carbon dioxide emissions associated with power plant construction are indicated to be 1% of the total for coal-fired electricity generation. Decommissioning is taken into account in the study but assumptions are not explicit and separate results are not presented. A list of 7 related studies, conducted between 1994 and 1998, is provided and brief reviews are included.

"Energy Content and Indirect Greenhouse Gas Emissions Embedded in 'Emission Free' Power Plants: Results for the Low Countries"
by K. R. Voorspools, E. A. Brouwers and W. D. D'haeseleer,
Energy Conversion and Applied Mechanics, University of Leuven, Belgium,
January 2000.

This study is reported in a paper which has been accepted for publication in Applied Energy in 2000. This review is based on a draft provided by the authors. The study compares the primary energy inputs and greenhouse gas emissions, measured in terms of equivalent carbon dioxide, of a nuclear power plant, onshore and offshore wind farms, and current and future photovoltaic cells. A combination of process analysis (based on physical data) and statistical analysis (based on financial data) is used to derive results for power plant construction, maintenance and demolition. The primary energy input to the construction, maintenance and demolition of the nuclear power plant is 6,216 to 18,944 GJ/MW(e) installed. Unfortunately, data for carbon dioxide emissions are not given separately but are incorporated in greenhouse gas emissions. Additionally, results for coal- and natural-gas fired power plants, quoted for comparative and reference purposes, are only presented graphically. There are also some unresolved differences with results from other studies. The original source of the results in this paper is not immediately apparent.

BIOFIT: Bio-Energy for Europe: Which Ones Fit Best"
by B. P. Weidema, P. H. Nielsen and A. M. Neilsen,
Denmark,
August 2000.

A brief account available on website: www.ipt.dtu summarises the results of this project which covers the entire life cycle of all relevant biofuels in comparison with fossil fuels. The work is funded by the European Commission under the FAIR Programme (Contract Ref. No. V CT98 3832) and involves partners from Austria, Denmark, France, Germany, Greece, Italy, Netherlands and Switzerland.

REFERENCES

1. "Modelling of Carbon and Energy Budgets of Wood Fuel Coppice Systems" by R. Matthews, R. Robinson, S. Abbott and N. Fearis, ETSU B/W5/00337/REP, Energy Technology Support Unit, Harwell, United Kingdom, 1994.

2. "Estimation of Carbon Dioxide and Energy Budgets of Wood-Fired Electricity Generation Systems" by R. Matthews and N. D. Mortimer, ETSU B/U1/00601/05/REP, Energy Technology Support Unit, Harwell, United Kingdom, 2000.

3. "Energy and Carbon Analysis of Using Straw as a Fuel" by J. F. Grant, R. Hetherington, R. E. Horne and N. D. Mortimer, ETSU B/M4/00487/01/REP, Energy Technology Support Unit, Harwell, United Kingdom, 1995.

4. "Carbon and Energy Modelling of Biomass Systems: Estimating the Energy Requirements and CO_2 Emissions from Production of the Perennial Grasses Miscanthus, Switchgrass and Reed Canary Grass" by M. Bullard and P. Metcalfe, ETSU 291, Energy Technology Support Unit, Harwell, United Kingdom, 2001.

5. "Carbon and Energy Modelling of Biomass Systems: Conversion Plant and Data Updates: Interim Report" by M. A. Elsayed and N. D. Mortimer, Report No. SCP 17/1, Resources Research Unit, Sheffield Hallam University, United Kingdom, 2000.

6. “Energy Analysis Workshop on Methodology and Conventions” International Federation of Institutes for Advanced Study, Report No. 6, Guldsmedhyttan, Sweden, August 1974.

7. “Workshop on Energy Analysis and Economics” International Federation of Institutes for Advanced Study, Report No. 9, Lidingö, Sweden, June 1975.

8. "Cost Data for Renewable Energy Systems" by D. J. Egan, M. Hulme and N. D. Mortimer, ETSU GEN 6069, Energy Technology Support Unit, Harwell, United Kingdom, 1992.

9. “Environmental Management - Life Cycle Assessment - Principles and Framework” European Standard EN ISO 14040, British Standards Institution, London, United Kingdom, 1997.

10. “Environmental Management - Life Cycle Assessment - Goal and Scope Definition and Inventory Analysis” European Standard EN ISO 14041, British Standards Institution, London, United Kingdom, 1998.

11. “A Review of the Potential of Biodiesel as a Transport Fuel” by F. Culshaw and C. Butler, Report ETSU-R-71, Energy Technology Support Unit, Harwell, United Kingdom, September 1992.

12. "A Review of Modelling of Carbon and Energy Budgets of Wood Fuel Coppice Systems" by N. D. Mortimer, Resources Research Unit, Sheffield Hallam University, United Kingdom, March 1994.

13. "Energy Expenditure Associated with the Production and Recycle of Materials" by J. C. Bravard, M. B. Flora III and C. Portal, Report ORNL-NSF-EP-24, Oak Ridge National Laboratories, New Mexico, United States of America, November 1972.

14. "Kirk-Othmer Encyclopaedia of Chemical Technology", John Wiley and Sons Inc., New York, United States of America, 1998.

15. "Energy Use in the Fertiliser Industry" Industrial Energy Thrift Scheme, Report No. 33, Department of Industry, London, United Kingdom, 1983.

16. “The Use of Energy Intensity Multipliers” by N. D. Mortimer, Report No. 22, Energy Workshop, Department of Physical Sciences, Sunderland Polytechnic (now the University of Sunderland), United Kingdom, January 1981.

17. "A Note on Carbon Dioxide Coefficients" by M. Grubb, Royal Institute for International Affairs, London, United Kingdom, 1988.

18. "Energy Analysis of the 'Report on the Census of Production, 1968'" by D. A. Casper, P. F. Chapman and N. D. Mortimer, Report ERG 006, Energy Research Group, The Open University, United Kingdom, 1975.

19. "An Input-Output Analysis of Carbon Dioxide Emissions for the UK" by R. Hetherington, Energy Conversion Management, Vol. 37, Nos. 6 – 8, pp. 979 – 984, 1996.

20. “Methodology for Environmental Profiles of Construction Materials, Components and Buildings” Centre for Sustainable Construction at the Building Research Establishment Ltd., CRC Ltd., London, United Kingdom, 2000.

21. "Digest of United Kingdom Energy Statistics, 1996" Department of Trade and Industry, HMSO, London, United Kingdom, 1997.

22. "Energy and Alternatives for Fertilizer and Pesticide Use" by Z. R. Helsel in 'Energy in Farm Production' edited by R. C. Fluck, Energy in World Agriculture, 6, Elsevier, Amsterdam, The Netherlands, 1992.

23. "Selecting the Right Fertilizer from an Environmental Life Cycle Perspective" by J. Kuesters and T. Jenssen, IFA Technical Conference, Marrakech, Morocco, International Fertilizer Association, Paris, France, May 1998.

24. "Energy Recovery by Crops in Dependence on the Input of Mineral Fertilizer" by S. Biermann, G. – W. Rathke, K. – J. Hülsbergen and W. Diepenbrock, Agroecological Institute and Institute of Agronomy and Crop Science, Martin-Luther University, Halle-Wittenberg, Germany, May 1999.

25. "The Energy Requirements of Cement for Use in the Construction of Wave Energy Devices" by G. Jenkins, Report No. 24, Energy Workshop, University of Sunderland, Sunderland, United kingdom, May 1981.

26. "Greenhouse Gas Inventory Reference Manual" IPCC Guidelines for National Greenhouse Gas Inventories, Vol. 3, Intergovernmental Panel on Climate Change, Hadley Centre, Bracknell, United Kingdom, 1995.

27. "Energy Analysis in the Assessment of the United Kingdom Wave Energy Programme, 1978" by R. Harrison, G. Jenkins and N. D. Mortimer, Report No. 18, Energy Workshop, University of Sunderland, Sunderland, United Kingdom, June 1980.

28. "Note on the Energy Requirements of Finished Steel Products" by F. Roberts, University of Sunderland, Sunderland, United Kingdom, 1978.

29. "Energy Analysis of Some Wave Energy Systems" by G. Jenkins, PhD Thesis, Department of Physical Sciences, University of Sunderland, Sunderland, United Kingdom, April 1984.

30. "Design of a 2.5 MW(e) Biomass Gasification Power Generation Module" by R. McLellan, Wellman Process Engineering Ltd, ETSU B/T1/00569/REP, Energy Technology Support Unit, Harwell, United Kingdom, 2000.

31. Talbotts product specifications, www.talbotts.co.uk, accessed 15 August 2000.

32. "Biomasseheizwerk Furth bei Landshut: Gemainde kombiniert Hackschnitzel und Solarenergie" C.A.R.M.E.N., Rimpar, Germany, October 1999.

33. "Energy Analysis of Burner Reactor Power Systems" by N. D. Mortimer, PhD Thesis, The Open University, Milton Keynes, United Kingdom, 1977.

34. “Life Cycle Analysis of Selected Biomass and Fossil Fuel Energy Systems in Denmark and Ghana - with focus on greenhouse gas emissions” by P. S. Neilsen, Report R-036, PhD Thesis, Department of Buildings and Energy, Technical University of Denmark, Denmark, 1996.