Life Cycle Assessment : New Zealand Merino Industry

Merino Wool Total Energy Use and Carbon Dioxide Emissions

Prepared by Andrew Barber and Glenys Pellow
The AgriBusiness Group

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Sustainable Farming Fund
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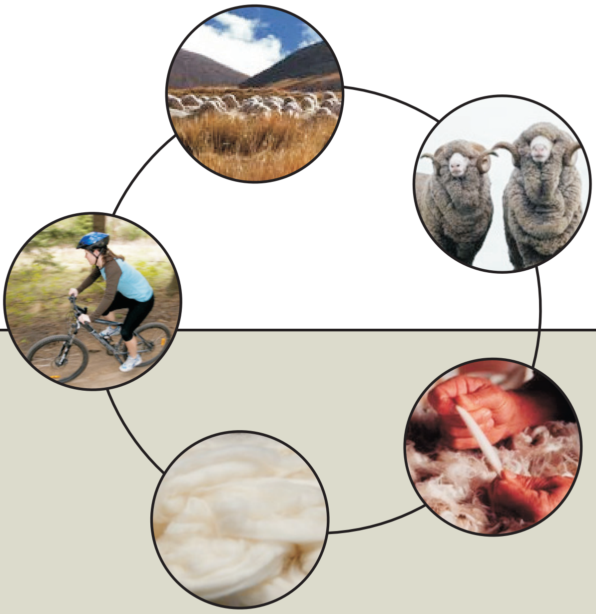

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Cover page provided by The New Zealand Merino Company.

CONTENTS

LIST OF ABBREVIATIONS

Energy and Power

J	joule	basic unit of energy	Factor
kJ	kilojoule	1,000 joules	E3
MJ	megajoule	1,000,000 joules	E6
GJ	gigajoule	1,000,000,000 joules	E9
TJ	terajoule	1,000,000,000,000 joules	E12
PJ	petajoule	1,000,000,000,000,000 joules	E15

W	watt	basic unit of power = 1 joule per second
kW	kilowatt	1,000 watts
kWh	kilowatt-hour	3.6 MJ

Others

ha	hectare	10,000 square metres
kg	kilogram	
t	tonne	1,000 kg
ℓ	litre	
ai	active ingredient	
DM	dry matter	
s.u.	stock unit	
s.s.u.	sheep stock unit	
CO_2	carbon dioxide	

EECA	Energy Efficiency and Conservation Authority
MAF	Ministry of Agriculture and Forestry
IPCC	International Panel on Climate Change
MED	Ministry of Economic Development

Wool Top	Wool top is the continuous, untwisted, ribbon of wool ('sliver') produced from the combing machine, after the fleece has been scoured and carded.
Gabi	An LCA software package www.gabi-software.com
SimaPro	An LCA software package www.pre.nl/

Conversions

1 ha = 2.47 acres
1 ℓ petrol = 0.90 ℓ diesel (diesel equivalents on an energy basis)
1 kJ = 239 calories
1 kW = 1.34 horse-power (HP)
1 MJ (primary energy) = 0.023 ℓ of diesel
1 MJ (consumer energy) = 0.028 ℓ of diesel

1.0 EXECUTIVE SUMMARY

New Zealand's natural competitive advantage is derived from the climate and efficient all year round outdoor pastoral farming systems which combine to make New Zealand wool products both environmentally and economically competitive.

The stunning scenery and images of a clean and green New Zealand environment are no longer enough; increasingly sophisticated customers want claims of environmental sustainability validated. This project aims to provide some quantitative information by conducting a Life Cycle Assessment (LCA) of merino wool and investigating the LCA literature on other fibres.

The merino wool LCA system boundary included the extraction of minerals, all aspects of the sheep farming operation, wool scouring, carding, combing and the shipping of wool tops to a spinning factory in China. The farming data was provided by surveying 24 merino sheep and beef farms, which were categorised as extensive, medium intensive and intensive operations. The wool processing and transport data was taken from published literature.

Total energy use was chosen as the impact category to investigate, as this is the impact category studied in most previous textile investigations and therefore allows a point of comparison. Carbon dioxide emissions, which are closely linked to energy use, were also determined as a measure of environmental impact.

Producing New Zealand merino wool fibre uses significantly less energy resource than it takes to manufacture fossil fuel dependent man-made fibres. For example, nylon manufacture uses over 5 times more energy, acrylic 3.8 times, and polyester 2.7 times more energy than it takes to produce the equivalent weight of wool fibre.

Included in the analysis was the energy cost to ship scoured wool to a spinning mill in China. Transport represented just 3% of the total energy cost. Half of the energy cost was attributed to farm production, with the rest being accounted for in wool scouring, top making and transport.

This project has produced a detailed inventory of New Zealand merino wool production that can be built upon by expanding the number of impact categories, conducting sensitivity analysis and determining environmental hotspots. Wool scouring is an area that requires further investigation in order to improve confidence in the data relating to this part of the production chain. The system boundary should also be expanded to encompass spinning, dying, apparel manufacture, customer use, and disposal.

The results are specific to New Zealand merino wool; other wool classes are likely to have different energy profiles due to differences in farming systems and farm productivity.

2.0 INTRODUCTION

The production of merino fibre in New Zealand is associated with stunning vistas and an expectation of environmental purity. The extensive grazing system employed by the majority of farmers lends to the minimisation of production inputs.

While farmers and marketers of New Zealand merino wool highlight their environmentally sustainable production systems, the market is demanding increased scrutiny and has an expectation that claims of sustainability and environmental performance can be validated.

The issue then becomes one of how substantially different materials, such as synthetic and natural fibres, including, wool, cotton, and linen (flax) which often perform similar functions, can be compared in a meaningful and valid way. All have an impact on the environment in their production, use and disposal.

This project was funded by MAF's Sustainable Farming Fund (www.maf.govt.nz/sff) and the merino industry organisation Merino Inc. The project has the following aims:

1. To establish baseline information on merino wool's overall resource use, energy consumption, and environmental impacts;
2. To determine environmental impacts;
3. To identify stages within the life cycle of merino wool production where a reduction in resource use and emissions might be achieved;
4. To help guide the development of new products, processes, or activities toward a net reduction in resource requirements and emissions, and;
5. Provide feedback to farmers and discuss likely options and their effects on productivity.

3.0 LITERATURE REVIEW

3.1 Life Cycle Assessment

3.1.1 What is Life Cycle Assessment?

The examination of a product or services life cycle started in response to increased consumer and government environmental awareness. The science emerged from studies that were conducted to determine a product's total energy use. These studies not only examined the direct or consumer energy that it took to manufacture a product but also took into account the energy to manufacture and deliver all product inputs such as chemicals, fertilisers, and capital equipment.

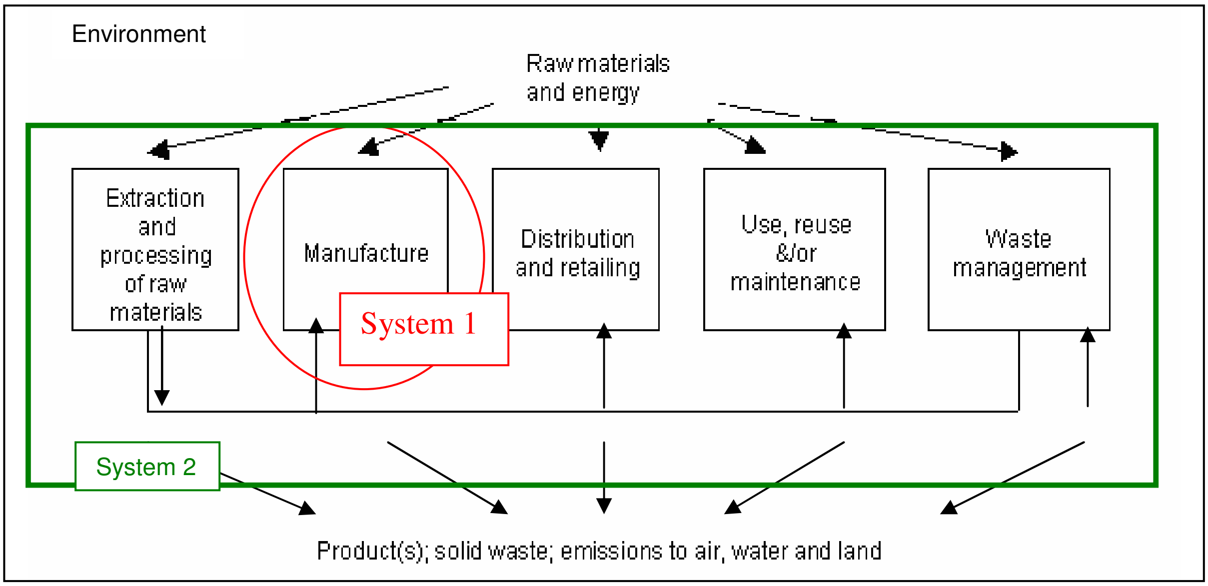
Life cycle studies were an extension of these and became vital to support the development of eco-labelling schemes and to quantify environmental claims.

A number of different terms have been used to describe LCAs. One of the first terms used was Life Cycle Analysis, although this has largely been replaced by Life Cycle Inventory (LCI) and Life Cycle Assessment (LCA) which better describe the two stage process of data collection and then interpretation of that data.

Linked with environmental concerns is the question of sustainable production. A whole production approach needs to be adopted that not only includes the production process itself but also raw materials, total energy use, environmental impacts throughout the supply chain, and how the final product is used, disposed of or recycled. Consideration of these components has lead to the concept of ‘cradle to grave’ assessments of environmental impacts (Cowell, 1999).

This concept is illustrated in Figure 1. The conventional approach to environmental assessment only considered the processing system, as illustrated by System 1. However, to assess sustainability it is necessary to consider the raw materials and product disposal, as shown by System 2. This creates a ‘cradle to grave’ analysis for environmental impacts of a product or service under analysis (Cowell, 1999). A product system is characterised by its function and includes unit processes, elementary flows, product flows across the system boundaries (either into or out of the system) and intermediate product flows within the system (AS/NZS ISO 14041:1999). The life cycle of a product is all the activities utilised in extraction of raw materials, design and formulation, production, processing, packaging, transportation, use and disposal of a product (European Environment Agency, 1997).

Figure 1 Generic Flow Diagram for Life Cycle Thinking and LCA



Source: Hodgson et al., 1997

Undertaking a Life Cycle Assessment involves a number of steps, which are outlined in the International Standards – ISO 14040:1998, 14041:1999, 14042:2001 and 14043:2001.

The functional unit of analysis is service driven so different systems providing the same service may be able to be compared (Cowell, 1999). However limitations of an LCA noted below (Section 3.1.4.9), need to be considered when making such comparisons.

3.1.2 Why Undertake a Life Cycle Assessment?

Both nationally and internationally, businesses discuss sustainable development of products and customers demand efficiency with which energy is used, raw materials utilised and waste minimised (European Environment Agency, 1997). This is part of a process through which responsible businesses look for ways to improve the eco-efficiency of products or services throughout their life cycle. Undertaking a life cycle assessment is a method used to address these responsibilities.

Narayanaswamy et al. (2004) consider LCA to be an environmental management tool that aims to decrease input costs and improve profitability with a reduction in environmental stress. An LCA can demonstrate a company's commitment to environmental management and can be used to identify, assess and prioritise environmental impacts within and across the business supply and demand chains. It should also highlight any trade-offs between improvements at one stage, and increased impacts at another stage (Cowell, 1999), and the process encourages multi-criteria assessment, thereby reducing the chance of single issue based decision making (Cowell, 1999).

LCAs focus managers' attention on those parts of the product life cycle that have the greatest contribution to environmental impacts. Having identified these hot spots it is possible for the industry or company to then prioritise which functions it will focus on to improve its environmental performance (Cowell, 1999). A well executed LCA can increase confidence in decision making around environmental management.

As an example of this, Arla Foods, a Scandinavian dairy manufacturer (Larsson, 2003), used the results of an LCA to provide answers to customers on environmental questions and to set targets for reducing milk losses within their production system. It also gave them a benchmark measure to avoid increasing the environmental impact of their packaging.

An LCA can give companies the opportunity to substantiate claims of a "clean and green" image. They can also complement and strengthen the implementation of other environmental programmes such as the Australian Environmental Management Standard. A well researched LCA, together with appropriate decision making tools and models, can lead to better environmental outcomes (Narayanaswamy et al., 2004).

3.1.3 What is involved in a Life Cycle Assessment?

To have confidence in the data collected and results of an LCA study, the ISO Standards 14040 to 14043 should be followed. This involves a number of steps as outlined below.

3.1.3.1 Defining the Goal and Scope

The planning stage of an LCA involves defining the purpose or goal of the study, the scope, the data quality goals and determining the functional unit. The product, process or activity is described and the system identified.

The goal should state the intended application of the LCA study, the reasons for undertaking the study and who the study is being undertaken for (AS/NZS ISO 14041:1999). The scope defines the boundaries of the study and these define the unit processes that are included in the system study. AS/NZS ISO 14041:1999 recommends that inputs and outputs at the boundaries are elementary flows; however, this may demand a study that is unachievable due to the depth of data collection that would be required.

The criteria used to set the system boundaries must be chosen with care to ensure that the goal of the study is achieved and the results can be used with confidence. Therefore in setting the goal it is necessary to determine which unit processes are included and the level of detail to which each is studied. It is not necessary to quantify inputs and outputs that will not significantly change the overall conclusions of the study. Decisions have to be made regarding which environmental emissions will be studied and in what detail. If life cycle stages, processes or inputs/outputs are omitted these decisions must be stated and justified. The system needs to be described in such detail that another practitioner could duplicate the inventory analysis.

An LCA study is an interactive technique and as such during the collection of information and data it may become obvious that the scope requires alteration to meet the study goal or even that the goal requires revising if unforeseen limitations or constraints arise or additional information is obtained. Where such a situation arises, it is necessary to document the changes and the justification for these.

3.1.3.2 Data categories

This is the stage to determine what data is to be collected and the environmental categories that will be examined. Data may be sourced from a mixture of measured data from the production site and calculated or estimated data from published sources.

3.1.3.3 Functional Unit

AS/NZS ISO 14041:1999 requires that the LCA scope includes a clear statement on the product's functions (performance characteristics). The functional unit defines and quantifies the identified functions and is to be consistent with the goal and scope of the study. The functional unit is measurable allowing it to be a reference to which input and output data can be normalised in a mathematical sense. Also the volume of product required to fulfil the function can be quantified and is referred to as the reference flow. The reference flow allows calculation of the inputs and outputs of the system and comparisons to be made between systems providing that the same function, functional unit and reference flow is used.

The functional unit allows comparison of data between similar stages. Also the environmental inputs/outputs should be partitioned and assigned to co-products in a multi-product system using either a mass or dollar value percentage between the co-products (Narayanaswamy et al., 2004).

3.1.3.4 Life Cycle Inventory Analysis

This stage requires identification and quantification of energy, water, materials and land usage, and environmental release data such as air emissions, solid waste emissions, water discharge etc during each life cycle stage (Narayanaswamy et al., 2004).

Data should be collected from specific sites (or representative averages) for the processes that contribute the majority of the mass and energy flows in the system being studied. The data collected needs to be validated and related to the unit processes and functional unit. The data can then be aggregated and if required the system boundaries refined (AS/NZS ISO 14041:1999).

3.1.3.5 Interpretation of the Life Cycle Inventory Analysis

The interpretation phase is for analysing the results including the identification of significant issues and explanation of limitations. An analysis of the results should consider the completeness of the data and include sensitivity and consistency checks.

The sensitivity check analyses the reliability of final results and conclusions by determining whether they are affected by uncertainties in any of the data, allocation methods or calculation of category indicator results. The consistency check also determines whether the assumptions made, methods used, and data, are consistent with the defined goal and scope.

The interpretation draws conclusions and provides recommendations based on the findings of the LCA. It also provides a readily understandable, complete and consistent presentation of the LCA study in conjunction with the goal and scope of the study (AS/NZS ISO 14043:2001).

3.1.3.6 Life Cycle Impact Assessment

In this stage, estimates are made of the likely human and ecological effects of material consumption, natural resource usage and environmental releases that have been estimated during the inventory analysis (Narayanaswamy et al., 2004).

The assessment phase provides a system wide perspective of environmental and resource issues for product systems. This allows for the inventory analysis results to be allocated to impact categories and an indicator result to be calculated. The indicator results give information on the environmental issues associated with the inputs and outputs of the system (AS/NZS ISO 14042:2001).

3.1.4 Limitations of a Life Cycle Assessment and Applicability of LCA studies to the Agricultural Industry

3.1.4.1 Data Variability

Dalgaard et al. (2003) commented that data for agricultural LCAs were often from a limited number of farms and therefore did not adequately account for the large variation in resource use by farmers or the environmental impact between farms within a sector.

A detailed LCA study of New Zealand Braeburn apple production (Milà i Canals et al., 2003) showed that there can be 30–50% variation in energy use between orchardists undertaking the same field operation due to differences in management technique, systems and physical site conditions. This highlights the considerable influence on inputs, outputs and emissions that orchardists' and farmers' individual management techniques exert.

The quality of data collected will have significant impacts on the accuracy of the LCA. Gaps in data collection or differences in allocation and aggregation procedures can limit the quality of results (Milà i Canals, 2003; AS/NZS ISO 14042:2001).

3.1.4.2 Site Dependency

LCA methodology has been developed for industrial sites contained within a building and therefore is often site-independent. An industrial system can often be located in any location and even any country. In contrast an agricultural operation is located on a particular parcel of land and as a result is heavily influenced by the specific land attributes, and related climatic and environmental factors.

An LCA of polyester manufactured in the USA could be compared to Asian manufactured polyester utilising the same environmental impacts with confidence. Agricultural operations vary significantly between different locations and hence the results of the different life cycle inventory analyses will most likely be significantly different (Milà i Canals, 2003).

Beaufoy's (2001) study of olive farming in the European Union confirmed that there are significant variations between agricultural production locations, especially in the physical and biological conditions of the site; grove characteristics, production systems and technology usage; and the socio-economic situation of the production unit.

In another analysis, Cowell and Clift (1997) discussed that site dependency aspects can have more influence on LCA results than activity dependent aspects. Krewitt et al. (2001) also concluded that site dependent data has a significant influence, especially in the impact categories of human health, acidification, eutrophication and man-made environment. However, Milà i Canals (2003) notes that there is some disagreement in the scientific community on the impact of site dependency.

Whatever the impact category, site dependency leads to limitations in the ability to consider all environmental impacts associated with agricultural production. This is due largely to the difficulty in assessing an input or output in isolation within the agricultural environment.

3.1.4.3 System Boundaries

Another difference between industrial and agricultural systems is the ability to define system boundaries. Industrial systems can often easily define their boundaries as the walls of the factory, whereas in an agricultural system there are aspects that occur outside of the system boundary but which impact inside, for example pollinating insect activity (Milà i Canals, 2003) and activities undertaken on neighbouring properties.

Although ideally LCAs should be 'cradle to grave' analyses, due to time, financial and data limitations, especially in agricultural systems where disposal of the product and lifetime usage is not part of the study, they are often a 'cradle to gate' analyses.

The LCA modelling system must be chosen with care to account for any knock-on effects of activities under analysis. This knock-on effect was considered by Milà i Canals (2003) in relation to activities that have occurred prior to the study period and continued to influence it after. Examples were residual nutrients from previous fertiliser applications, and the question of how to view the soil. Given that soil is a living system, only some aspects will be considered as part of an LCA study. These factors influence the way in which allocations of inputs are dealt with (Milà i Canals, 2003).

Additionally, both Cowell (1998) and Milà i Canals (2003) raised the issue of time boundaries. In a complete 'cradle to grave' agricultural LCA study this can be very relevant as activities in the past affect actual productivity, for example, full crop rotations and whole tree life cycles. Therefore, studying the system for the full lifetime of animals can be important to accurately analyse environmental impacts in an agricultural system.

3.1.4.4 Other Impacts

LCAs are time consuming and expensive to undertake if primary data is to be gathered and results interpreted in a way that provides meaningful information. However they do provide insight into the environmental impact of various processes in a production chain (De Boar, et al., 2003).

Undertaking a full LCA will give the greatest information to assist in decision making but could lead to an overload of data in addition to considerable expense and time implications. To deal with these pragmatic issues, a simplified LCA is often undertaken with a clearly defined scope (European Environment Agency, 1997).

LCAs are a relatively new field of environmental standard, especially in the agricultural industry, so consequently it has not yet been shown whether results are repeatable. Also, Milà i Canals (2003) identified that the LCA methodology has not determined conclusively how to allocate emissions of renewable carbon and carbon fixation by plants.

3.1.4.5 System Knowledge

Detailed knowledge of a system and the interactions between elements within it influences the accuracy of a life cycle assessment. As stated by Milà i Canals (2003), humans have designed industrial processing systems and the functions are well understood. In contrast, agricultural production involves natural eco-systems which have been modified as a means to achieve an economically viable product. In these systems, our knowledge of the complexities and interactions between elements is limited, and the biological processes embedded within agricultural eco-systems are complex and can be unpredictable.

3.1.4.6 Allocation Issue

When undertaking an agricultural life cycle inventory analysis, allocation is often a problem that must be addressed. Many agricultural systems are multi-functional and produce multiple products; therefore the inputs and outputs need to be apportioned between the various products. By comparison, industrial systems either produce one product or, if multiple products are produced, there is usually a clear physical or economic relationship that easily separates the allocation of inputs and impacts (Milà i Canals, 2003).

3.1.4.7 Data Uncertainty Analysis

Milà i Canals' (2003) study of apples discussed the impact of uncertainties they found in the data collected and the impact on their results. In this particular study the uncertainties were large, limiting confidence in the results. Particular issues surrounded pesticide biodegradation half-lives, volatilisation values, machinery lifetime, and emissions from tractors. They identified the need to collect specific information on machinery usage in LCA studies, including how machines are used on farms, as the energy required to manufacture and service machinery accounted for 7–15% of total energy consumption. They also found a need to reduce model uncertainty for nitrate leaching, pesticide leaching, and the retention of heavy metals from fertilisers and pesticides in soils.

3.1.4.8 Assessing Impact on the Environment

It is important to note that Life Cycle Inventory Analysis is looking at the inputs and outputs of the system and not their impact on the environment (AS/NZS ISO 14041:1999). Therefore, care needs to be taken in drawing conclusions about the impacts on the environment. This reiterates the importance of a precise scope for the LCA, as the scoping phase assists in defining the limitations of the study and the data collected. The scope also defines which environmental impacts will be studied (AS/NZS ISO 14042:2001) in the Life Cycle Impact Assessment.

There are also a number of environmental impacts that are not assessed easily using an LCA, such as land use, soil quality, biodiversity, and animal welfare. These can potentially have major impacts on the production system (Milà i Canals, 2003).

3.1.4.9 Comparison between products

Whole industry LCAs consider the activities occurring at a number of sites, however each site will vary in its impact on the environment. LCAs are more suited to comparison between two identical sites rather than across an industry. Milà i Canals (2003) also noted a lack of consistency and standardisation of methodology between different projects for agricultural environmental analysis, leading to difficulties in transferability and relevance under differing conditions. Caution needs to be exercised when comparing agricultural systems with different sets of indicators. For an accurate comparison between two different products, the same environmental impacts must be selected, and the same methodology and functional unit used (AS/NZS ISO 14042:2001).

AS/NZS ISO 14042:2001 recommends analysing the results of an LCA for sensitivity. This measures the influence, which changes to inputs/outputs have on the indicator results, and uncertainty, which determines the statistical variability in data sets, when a comparison between two products is required. It may be necessary to undertake other studies to provide full information on environmental impacts when making comparative statements. The undertaking of sensitivity and uncertainty analysis to compare two products is only possible when you have a complete set of raw data for each product.

The European Environmental Agency (1997) recommends that LCAs are not used to claim a product or service is environmentally friendly or superior to another. It is possible to claim that using a specified set of criteria one product is better than another in certain aspects of its performance. However if making such claims it is very important that accurate data and unbiased information is used, the assessment has been peer reviewed, and not to over-claim.

3.2 Life Cycle Assessments in the Textile Industry

A small number of LCA studies have been undertaken on textile products. Unfortunately many do not include a detailed inventory. This reduces the confidence in using such figures for comparative studies.

When considering a comparison of different fibres it is necessary to consider that they are very different products and often have different end uses. Due to these differences care must be exercised when comparing LCA results between products. It is also important to note that the environmental impact of the maintenance phase (garment care and laundering) of the product by the user of a textile often exceeds that of the manufacturing process, so ideally this should be included in a LCA study (Laursen et al., 1997).

An Ecological Footprint study on cotton, hemp and polyester (Cherrett et al., 2005) aimed to “determine the land area to provide all the necessary resources and absorb the associated carbon dioxide waste required to produce a given unit of textile and within the context of the Earth’s biological capability to regenerate those resources”. The study found that the available production data for these textiles and the quality of that data varied, especially for cotton, which is grown under a range of production practices and in different countries. Technological efficiency gains also affect the consumption data and hence the results. Results from this, and other relevant studies are included in Table 1.

3.2.1 Total Energy Use

Total energy use for textile fibre production is summarised in Table 1, with a detailed description of the studies that this information was based on provided in Appendix 1.

Table 1 Textile Fibre Energy Use

Textile	**Energy consumption (MJ/kg fibre)**
Nylon	250
Acrylic	175
Polyester	125
Polypropylene	115
Viscose	100
Cotton	55
Wool	63 †

† This project calculated a lower wool production value of 46 MJ/kg wool top (23 MJ/kg was on-farm).

3.2.1.1 Nylon

Of the fibres that Wiseman (1981) studied, nylon had the highest energy requirement at 222 MJ/kg. The British Textile Technology Group (BTTG) report (1999) calculated the energy requirement as 260 MJ/kg with an additional 63 MJ/kg for texturing, winding, warping and knitting. The GaBi database presents a figure of 262 MJ/kg.

3.2.1.2 Acrylic

Acrylic is the artificial fibre that most resembles wool, which is the reason why it is often applied alone or mixed with wool in different products that have historically been manufactured exclusively of wool. The major end uses for acrylic fibres are apparel (65%), home furnishings (30%) and industrial use (5%) (Laursen et al., 1997).

Both Laursen et al. (1997) and Wiseman (1981) calculated similar energy inputs of 157 and 165 MJ/kg respectively for acrylic production. The GaBi database presents energy inputs in the production of acrylic (Polymethyl methacrylate or PMMA) through to the granulate stage as 194 MJ/kg. Fabric manufacture may add another 15 MJ/kg (see Section 3.2.1.3 below).

3.2.1.3 Polyester

Polyester is a man-made fibre derived from petroleum oil. In 2001 it accounted for 32% of the world's fibre production. Its popularity is due to its stretch resistance, thermal stability and low moisture absorption properties (Cherrett et al., 2005).

Franklin Associates (1993) found that polyester requires energy inputs of around 112 MJ/kg fibre, and emits large volumes of air and water borne emissions. Of this, 97 MJ is from resin (raw material) manufacture, and 15 MJ is from fibre manufacture. Beyond the boundaries of this study an additional 87 MJ/kg is required for fabric production and 8 MJ/kg for apparel production. Cherrett et al. (2005) found similar energy inputs for polyester production of 104 MJ/kg in Europe and 127 MJ/kg in USA.

Wiseman's (1981) values were slightly higher at 138 MJ/kg. The GaBi database output is higher again at 148 MJ/kg.

3.2.1.4 Polypropylene

Polypropylene is used to produce film from which fibres and yarns are made. Examples of the end us of polypropylene include woven tape fabrics such as shade cloth, rope and twine, tufted carpet, tufted carpet backing and apparel products.

Wiseman (1981) found the production energy input was 117 MJ/kg.

3.2.1.5 Viscose

Viscose fibres are regenerated cellulose fibres, mainly derived from wood as the raw material. They are usually produced from sulphite based pulping processes. Viscose is widely used in textiles, especially blended with synthetic fibres to provide moisture absorption.

Energy use in the production of viscose fibre is around 100 MJ/kg (Wiseman, 1981). This is similar to the aggregated figure for wood production to pulp of 26 MJ/kg (Laursen et al., 1997) and wood pulp to fibre of 82 MJ/kg (Woodings, 1993). MoDo (1995) found the energy use in the production of wood for one kilogram of viscose fibre to be 36 MJ/kg.

3.2.1.6 Cotton

The production of cotton fibre requires a large volume of water and fertiliser inputs, especially nitrogen, as well as pesticide inputs. Management practices vary considerably within a country and around the world. Hence input usage and management systems will affect the results of LCA studies.

The management system can influence the inputs required, for example, the use of harvest aid chemicals which increase harvest efficiency and decrease foliage and moisture levels. The harvesting system will affect the volume of foreign matter present with the seed cotton and affect the ginning of seed into cotton fibres with respect to energy consumption and waste (Laursen et al., 1997).

Van Winkle et al. (1978) determined that the total net energy for producing conventional cotton lint was 49 MJ/kg. This included electricity and fuel for growing and ginning, and the energy required for manufacturing the fertiliser and pesticides.

Kalliala and Nousianinen (1999) found energy consumption for conventional cotton fibre was 60 MJ/kg and for organic cotton was 54 MJ/kg. Both Cherrett et al. (2005) and Wiseman (1981) found much lower energy inputs of 26 MJ/kg and 29 MJ/kg respectively for conventional cotton. Cherrett et al. (2005) also found that organic cotton grown in the USA and produced through to a spun fibre required just 13 MJ/kg.

3.2.1.7 Wool

A 1995 study by Nguyen, determined that the energy consumption for sheep meat and wool production was 1,000 MJ/ha and that the energy required to produce 1 kilogram of greasy wool was calculated as 8 MJ/kg. This was based on a stocking rate of 10 sheep per hectare, 5 kilograms of greasy wool per sheep and 40% of the inputs being allocated to wool. Wiseman (1981) reports a wool production figure of 38 MJ/kg.

The environmental textile review conducted by Laursen et al. (1997) found no information on energy use to scour greasy wool. Since then energy figures have been published by Bremer Woll-Kämmerei AG (BWK) as part of their Environmental Statement in 1999 and 2002. Total primary energy for scouring, drying and combing was 25 MJ/kg output and rose to 33 MJ/kg in 2001 when production dropped by a third. The British Textile Technology Group reports a lower figure of 15 MJ/kg (BTTG, 1999).

3.2.2 Carbon Dioxide Emissions

Most of the textile reports that have been referenced for total energy use have not calculated carbon dioxide emissions. Franklin Associates (1993) in their study of a polyester blouse did not determine carbon dioxide emissions, however based on their inventory of fuel types and the carbon dioxide emission factors described in Table 2 the carbon dioxide emissions can be calculated with the results shown in Table 3.

Table 2 Carbon Dioxide Emission Factors

Fuel Type	**g C/MJ**	**g CO_2/MJ**
Natural Gas	14.3	52.3
Petroleum (diesel)	19.0	68.7
Coal	24.1	88.5 †

Source: Brown and Petrie, 2005

† Coal has a CO_2 emission factor of 91.3 g CO_2/MJ of consumer energy, which when the 23% fugitive diesel emissions for mining, processing and transport are included lowers the overall coal CO_2 emission factor to 88.5 g CO_2/MJ primary energy.

Table 3 Carbon Dioxide Emissions from Polyester

	Total Energy Use (Megajoules, MJ)					**Total CO_2 (kg)**
	Natural Gas	**Petroleum**	**Coal ‡**	**Other**	**Total**	
PET Resin						
1 blouse	1.64	2.71	0.58	0.30	5.24	0.33
1 kg polyester	30.41	50.27	10.79	5.55	97.02	6.04
Fibre Manufacture						
1 blouse	0.08	0.10	0.39	0.21	0.78	0.05
1 kg polyester	1.41	1.88	7.27	3.91	14.46	0.86
Total kg CO_2/kg	**1.67**	**3.62**	**1.60**	**0.00**	**-**	**6.89**

Source: Franklin Associates (1993). Energy use converted from BTU to MJ.

‡ Assumed 23% of total energy is fugitive emissions from mining and transport which the CO_2 emission factor for diesel was applied to.

Based on these calculations and Franklin Associates (1993) energy use of 112 MJ/kg, the average carbon dioxide emission factor for polyester is around 62 g CO_2/MJ.

Based on the same average carbon dioxide emission factor, nylon with a total energy use of 250 MJ/kg has an emission of 15 kg CO_2/kg nylon.

No previous wool studies were found that determined the carbon dioxide emissions or provided enough detail on the mix of fuel sources to calculate the emissions.

4.0 STUDY GOAL AND SCOPE

4.1 Goal of the Study

The goal of this project was to:

1. Develop detailed resource input and output data for New Zealand merino farms;
2. Assess the environmental impact of merino wool production and compare this to published data on other common textiles, and;
3. To provide the New Zealand Merino Industry with a better understanding of Life Cycle Assessments.

4.2 Functional Units

Two functional units have been used. The main unit throughout the report is a "*tonne of dry wool top*". Wool top is the continuous, untwisted, ribbon of wool ('sliver') produced from the combing machine, after the fleece has been scoured and carded. The combing process removes short /weak fibres ("noils") leaving long fibres which are aligned parallel to one another. This is the highest quality or "top-of-the-line" wool fibre, hence the name "top". Only wool to be used for worsted yarn goes through the combing process. Wool to be used for woollen yarn is scoured and carded, but not combed.

Weight of wool top is measured as the clean, dry wool fibre. The weight of wool in an end product will include water that has been regained after the wool drying process. As this moisture regain can vary, the functional unit is dry fibre.

The energy per tonne of wool top including regained moisture from the atmosphere will be approximately 9% lower than the results presented in this report as a result of the difference in weight.

For the on-farm aspect of the study, the functional unit is both a tonne of wool top and a "*tonne of greasy wool*".

Two units were chosen to ensure that different audiences could relate to the functional unit, and ensure that the on-farm aspect of the study could stand alone without having to understand the allocation rules and system boundaries of wool processing.

4.3 System Boundary

4.3.1 Included

Figure 2 shows a simplified life cycle diagram for wool production. The dotted line is the boundary between the environment and the production system.

The system boundary includes the impacts associated with:

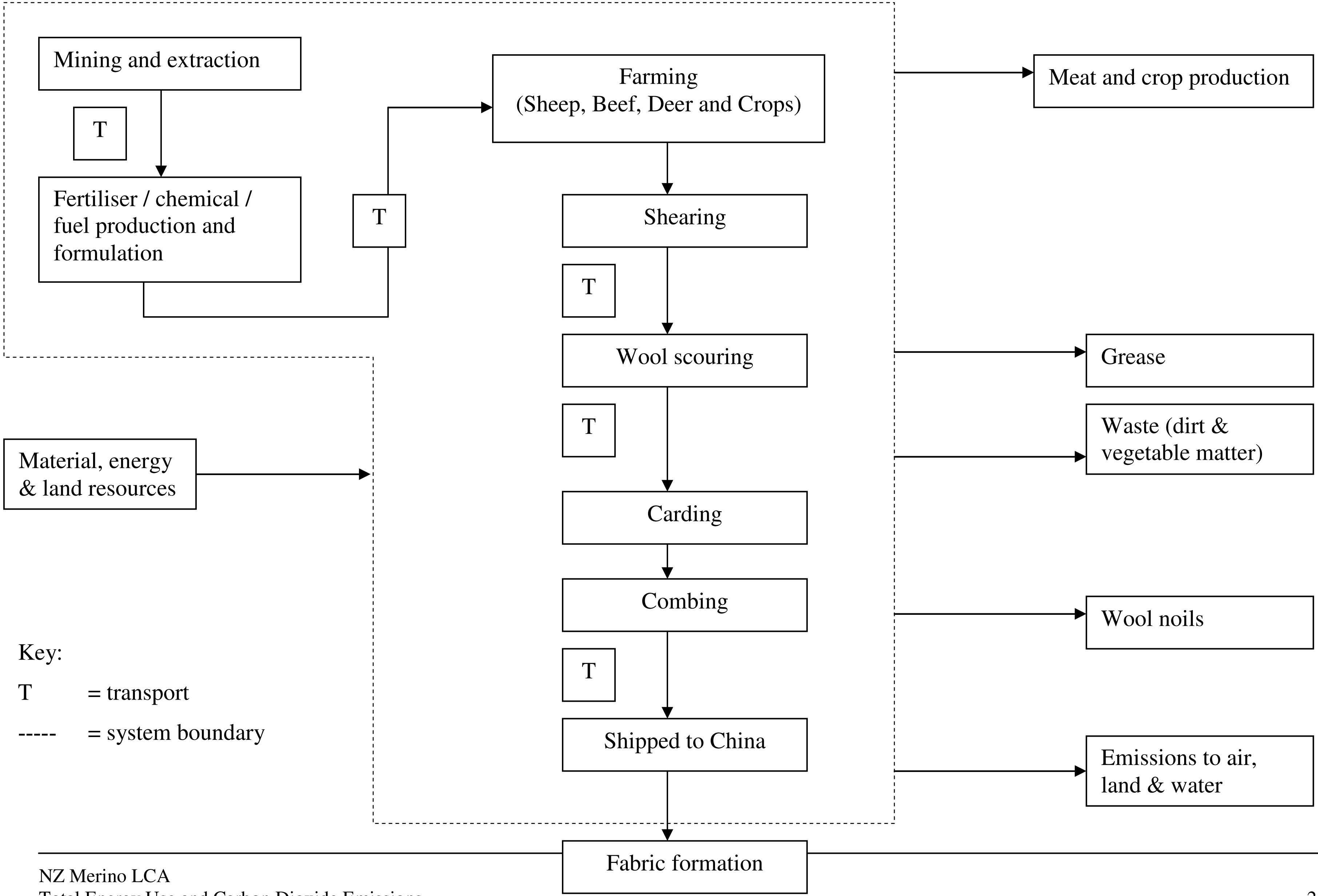
- The extraction, refinement, formulation, packaging and transport to the farm of fuel, fertiliser and agrichemicals;
- Fuel use on the farm which includes both what the farmer purchases as well as the estimated fuel use by contractors. Typical activities carried out by contractors included aerial fertiliser application, cultivation, direct drilling and silage making;
- On farm electricity use, mainly for irrigation and minor uses like shearing and some water reticulation. Electricity included fugitive losses in conversion and distribution;
- Fuel and electricity use during wool scouring, carding and combing;
- Transport of wool by truck between the farm and the closest New Zealand port, and;
- Transport by ship between New Zealand and China.

4.3.2 Excluded

The components of the life cycle which have been excluded are:

- The embodied energy and emissions from capital equipment;
- Carbon sequestered in soil and farm products;
- Wool packaging, which is usually bales wrapped in nylon and held together with steel strapping or wires, and;
- Further stage processing such as spinning (yarn manufacture) and knitting/weaving (fabric manufacture).

Figure 2 Life Cycle of New Zealand Wool to Fabric Formation



4.4 Allocation

Merino farms in New Zealand are mixed production systems that, apart from merino sheep, also include one or more of cattle, deer and or cropping systems. Each system is intertwined and integral to improving the overall productivity of the whole farm. Hence the inputs are aggregated as a total for the farm and are not separately allocated to the individual animal or crop types, even for the few instances where this may be possible. For example, electricity for irrigating crops is still divided over the whole farm production system rather than just allocated to the cropping system. This is because a paddock being grazed may have benefited from having an irrigated crop grown in it the previous year in terms of improved soil structure and fertility.

The proportional allocation of inputs to systems with multiple outputs can either be done on a weight or financial basis. The financial approach is susceptible to marked variations in price between locations and times. Farm profitability and revenue streams can be cyclical and for an exporting country like New Zealand are often dependant on world commodity prices and the exchange rate.

Consistent with the ISO 14041:1999 standard, where allocation can not be avoided, farm inputs are based proportionally on the underlying physical relationships between them. In this study the weight of the three key production outputs; animal carcases, greasy wool and cash crops (often barley) was used. Animal carcass weight was chosen, rather than live weight, as this better reflects what the farmer is paid.

While it varied between farms, wool was approximately 25% of the total output weight when carcass weight was used. If the total farm output was based on animal live weight, then wool was reduced to around 15% of output by weight.

The use of carcass weight effectively increases the energy costs allocated to wool. This is a conservative approach and it is closer to what the financial allocation would have been. While no financial data was collected in this study the MAF Merino Model (MAF Farm Monitoring, 2005) states revenue derived from wool as approximately 50%. The farms in this study would have less wool revenue as merino comprised on average 76% of the wintered animals compared to 87% in the MAF farm monitoring model. In addition to this the ISO standard 14041:1999 only recommends using allocations based on economic values where physical relationships alone cannot be established.

Beyond the farm gate all transport was allocated to wool.

In the wool scouring and top making stages inputs were allocated proportionally based on the weight of the economic outputs of wool, the by-products of grease, which is further refined into lanolin, and wool noils which are used in the production of less expensive woollen fabrics and felt.

4.5 Data Categories

Two types of data collection were used. The primary data was collected directly from farmers and processors. Farmers provided the following information:

General
- Effective area
- Stock reconciliation
- Cultivated area and type of cultivation
- Quantity of silage produced

Inputs
- Electricity
- Liquid fuel
- Contractor operations (type of operation, time taken or area covered)
- Fertiliser
- Chemicals
- Purchased feed

Outputs
- Wool
- Stock sales
- Crops

One wool top maker provided information on:

Inputs
- Scoured Wool
- Electricity

Outputs
- Wool Top
- Solids (dirt and vegetable matter)

Background data came from published sources. Most of the background data relates to the calculation and application of energy and emission coefficients. Some data gaps were filled through communication with people in the industry.

Background data included:

- Mining and extraction
- Fertiliser and chemical formulation, packaging and transport
- Electricity production and distribution losses
- Transportation
- Contractor fuel consumption rates
- Wool scouring

5.0 METHODOLOGY

5.1 Farm Description

5.1.1 Farm Category

Each of the 24 farms surveyed was categorised as either extensive, medium intensive, or intensive. The split was made so that there were eight farms in each category. The farms were ranked based on their stocking rate with the farms with the eight highest stocking rates assigned to the intensive category, the next eight farms to medium intensive and the eight lowest stocking rates to the extensive category.

The extensive farms had an average stocking rate of 0.94 s.u./ha, ranging between 0.70 and 1.30 s.u./ha. The medium intensive farms averaged 2.64 s.u./ha and ranged between 1.92 and 3.42 s.u./ha. The intensive farms averaged 7.40 s.u./ha and ranged between 3.45 and 13.66 s.u./ha.

5.1.2 Stocking Rate

Livestock in New Zealand are commonly given a ‘stock unit’ (s.u.) value. The basic unit (one stock unit) is one breeding ewe that weighs 55 kg and bears one lamb. This ewe consumes approximately 550 kilograms of dry matter per year. Other livestock are measured against this standard, for example, a cow commonly has a value of 6 stock units. In other words they consume approximately six times the amount of feed as a ‘standard’ ewe over a year (Fleming, 2003).

The number of each stock class wintered was collected from the farmers, together with stock purchases and sales. The figures given in the survey did not always balance so the farm management program Stockpol was used to reconcile the numbers [1].

Stock class and stock unit values are presented in Table 4.

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[1] Stock reconciliation conducted by Stuart Edwards

Table 4 Stock Units

Stock Class	**Stock Unit**		**Stock Class**	**Stock Unit**
Sheep			**Deer**	
Ewes	see calculation below		Hinds	1.9
Wethers	0.7		Rising 1 year deer	1.8
Hoggets	1.0		Stags	2.8
Beef Cattle			Weaners	1.3
Cows	6.0			
Rising 1 year heifers	3.5			
Rising 1 year steers	4.0			
Rising 2 year heifers	4.5			
Rising 2 year steers	5.0			
Bulls	6.0			

Source: Fleming, 2003. Farm Technical Manual

The ewe stock unit measurement was based on a 55 kg ewe at mating and the percentage of lambs weaned. This was calculated using the following equation:

$$Total\ farm\, ewe\ stock\ units = No.\ of\ \ ewes\ x\ (0.5\ x \left(\frac{lambing\ \%}{100} \right) + 0.5)$$

Dividing the total farm ewe stock units by the number of ewes gives the average ewe stock unit value.

5.1.3 Purchase and Sale of Stock

The number of animals purchased and sold, plus their live weight, was collected in the farmer survey.

Most farms only had minor stock purchases, although one farm purchased a large number of lambs. The farm output in meat was calculated as net sales to take into account that proportion of the stock that were raised on other properties.

It was assumed that all stock sales were eventually destined for the meat works. While this is not always true, it is in the vast majority of cases. Both purchases and sales were converted from live weight figures into carcass weights. Although farmers do not purchase stock based on their carcass weight the effective carcass weight at the time of purchase was used to determine the meat gain that occurred on the survey farm.

The carcass weight was calculated based on the animals live weight at purchase or sale, and the dressing out percentage.

Sheep dressing out percentage was calculated from the equation:

$$DO\% = \frac{HCW\ x\, 100}{liveweight}$$

$$Hot\ Carcass Weight\ (HCW) = 0.50\ x\ full\ liveweight - 2.01$$

Source: AgFact, 1997

The average sheep dressing out percentage in this study was 45%.

Beef was assumed to have a dressing out percentage of 56%, based on the data from steer processed at Manawatu Beef Packers (Charolais, 2005). Deer dressing out percentage was 58%, based on red deer ranging between 51 and 65% (De Vos, 1982).

5.1.4 Crop Sales

Three of the farms sold either barley or carrot seed. The harvested weight of the grain and seed was included in those farms total output weight.

5.1.5 Wool Sales

All farms reported their total greasy wool sales in tonnes.

5.2 Total Energy Use

Total energy use is calculated using primary energy values. This is the sum of consumer energy plus all the energy used or lost in the process of transforming energy into other forms and in bringing the energy to the final consumers. Consumer energy is defined as the amount of energy consumed by the final user, for example the kilowatt-hours recorded on the electricity meter or the actual energy value of fuel available to an engine.

When calculating total energy use it is necessary to use primary energy, so that both direct and indirect energy sources are being accounted for on the same basis.

5.2.1 Farm Direct Energy Inputs

5.2.1.1 Diesel and Petrol

The gross energy content or consumer energy of diesel and petrol is 36.1 and 32.5 MJ/ℓ respectively (MED, 2005). The primary energy content, which includes an allowance for the fuel's production and delivery, adds an extra 23% (Wells, 2001). This makes the total energy content for diesel and petrol 44.3 and 40.0 MJ/ℓ respectively. These figures are summarised in Table 5.

All fuel used was recorded; no distinction was made between business and personal use in the survey. It was then assumed that personal fuel use accounted for 1,500 litres of petrol, based on approximately 15,000 km of travel at 10 litres per 100 km's.

Any reference to liquid fuels in this report refers to the aggregated figure of diesel and petrol. Some farms used petrol for road vehicles and this was converted into equivalent litres of diesel on the basis of energy content. The conversion used was 1 litre of petrol equals 0.90 litres of diesel.

The quantity of lubricants used was not collected, as it was considered insignificant.

Table 5 Energy Values of Direct Fuel Inputs

Fuel	Energy Units	Energy $_{consumer}$	Fugitive Multiplier	Energy $_{primary}$
Diesel	MJ/ℓ	36.1 [a]	1.23 [b]	44.3
Petrol	MJ/ℓ	32.5 [a]	1.23 [b]	40.0
Electricity	MJ/kWh	3.6	2.04	7.3

Data sources:
[a] NZ Energy Data File 2005 (MED)
[b] Wells, 2001

5.2.1.2 Electricity

The consumer energy content of electricity is 3.6 MJ/kWh. Based on electricity generation in 2004 of 291 PJ and consumption of 143 PJ (MED, 2005) the primary energy content is much higher at 7.34 MJ/kWh. This takes into account electricity conversion losses in generation (137 PJ) and transmission losses (11 PJ). It takes 2.04 kWh of primary energy to supply 1 kWh to the consumer. This is an improvement on what Wells (2001) reported of 8.18 MJ/kWh (2.27 primary to consumer energy) based on 1997 data and Barber (2004a) of 8.14 MJ/kWh based on 2002 data. The 2005 figure is shown in Table 5 above.

New Zealand has well established renewable energy sources, the main two being hydro and geothermal. In 2004 64% of electricity generation came from renewable sources (MED, 2005).

5.2.1.3 Fuel Use by Contractors

Fuel use by contractors was calculated from the type and amount of work that they carried out.

It was not apparent from the survey results what work had been conducted by contractors versus that completed by the farmer, and hence what fuel had already been accounted for. It was assumed that all cultivation, fertiliser spreading and feed (hay, silage and forage) production was carried out by a contractor. This is certainly likely to be true for aerial topdressing, direct drilling and silage making, however it may lead to double counting of fuel inputs for activities like conventional cultivation, which the farmer may have undertaken themselves.

Fuel consumption data has been developed by McChesney (1981) and Bone et al. (1996) for various agricultural activities and the adapted results were presented by Wells (2001). Adaptations in this study to the Well's results include a single per hectare fuel cost for conventional cultivation of arable type crops of 80 ℓ/ha (Barber, 2004a) and direct drilling at 20 ℓ/ha, based on savings of 80% compared to conventional cultivation (Barber and Pellow, 2005). Wells reported aerial topdressing at 7 ℓ/ha, which appears to be very high. This study uses a rate of 1.1 ℓ/ha of aviation fuel (Sinclair pers. comm., 2005).

Table 6 describes contractor activities and their fuel use.

Table 6 Average Diesel Consumption Rates for Agricultural Operations

Activity	Fuel Use	Activity	Fuel Use
Conventional cultivation	80 ℓ/ha	Forage harvesting	2 ℓ/t
Direct drilling	20 ℓ/ha	Ground fertiliser spreading	3 ℓ/ha
Mowing	6 ℓ/ha	Aerial topdressing	1.08 ℓ/ha
Raking	2 ℓ/ha	Road cartage	0.069 ℓ/tonne-km
Bailing	2 ℓ/t		

5.2.2 Farm Indirect Energy Inputs

5.2.2.1 Fertiliser

To calculate the energy cost of each fertiliser they were broken down into their different nutrient components.

Table 7 shows the average energy costs of manufacturing each component (Wells, 2001). These are average figures taken from a range of different fertiliser production methods.

Table 7 Energy Requirements to Manufacture Fertiliser Components

Component	Energy Use (MJ/kg)
Nitrogen (N)	65
Phosphorus (P)	15
Potassium (K)	10
Sulphur (S)	5
Magnesium (Mg)	5
Lime	0.6

Where the application of lime was not part of an annual programme the amount applied was apportioned over the number of years between applications. It is possible that some lime applications were not recorded if they had not been applied during the year being surveyed and the farmer was not asked about previous capital applications.

5.2.2.2 Agrichemicals

The energy requirement to manufacture agrichemicals ranges between 100 to 200 MJ/kg of active ingredient (ai). Energy used in formulating, packaging and transporting the chemicals adds a further 110 MJ/kg ai. Table 8 shows the energy input for various agrichemical categories. The herbicide, insecticide and fungicide figures have been adapted from the Handbook of Energy Utilisation in Agriculture (Pimentel, 1980) having removed the formulations that have been withdrawn from the market.

Animal remedies were assumed to have a total energy input of 210 MJ/kg ai, adapted from Wells (1998).

Some studies, such as Milà i Canals (2003), have gone into greater detail to determine more accurately the exact embodied energy cost of individual agrichemicals. As chemical use is only a minor component, being less than 2% of total on-farm energy use, that was considered unnecessary for the purpose of this study.

Table 8 Energy Inputs for Various Agrichemicals

Agrichemical	Production of active ingredient (ai)	Formulation, Packaging and Transport	Total (MJ/kg of ai)
Animal remedies	100	110	210
Herbicide	200	110	310
Insecticide	185	110	295
Fungicide	100	110	210
Other	100	110	210

5.2.2.3 Purchased Feed

Most farms produced their own silage or hay as supplementary feed. The cost of this is taken into account through the use of inputs such as diesel and fertiliser. Many farms also purchase additional feed, normally barley, although one farm in this study also purchased silage and hay. The cost of this purchased feed needs to be accounted for. The embodied energy of these inputs is shown in Table 9.

Barley has a total energy cost of 34,150 MJ/ha (Barber, 2004a) or 31,360 MJ/ha if capital inputs are excluded to remain consistent with the methodology used in this study. Based on a yield of 8.8 t/ha of grain and 4.4 t/ha of barley straw (Barber, 2004a), the embodied energy in the grain is 2,375 MJ/t. With an average grain dry matter (DM) content of 85% (Wrightson, 2005) the energy content is 2,795 MJ/t DM.

Silage has an energy content of 1,500 MJ/t DM (Wells, 2001) and hay, assuming the same energy requirement as silage, is 27 MJ/small bale. A small hay bale was assumed to weigh 21.5 kg and have a dry matter content of 85%.

Table 9 Embodied Energy Content of Purchased Feed

Feed	MJ/unit	units	MJ/t DM
Grain (barley)	2,375	tonne	2,795
Silage	1,500	tonne dry matter	1,500
Hay	27	small bale	1,500

5.2.3 Wool Transport

5.2.3.1 Truck

Road cartage is 0.069 ℓ/tonne-km (Barber, 2004a), fractionally less than the figure of 0.079 ℓ/tonne-km reported by Wells (2001) and is based on actual data.

The farm survey asked how far the farm was from the port. It was then assumed that the wool was transported to the port for export, with the wool processing plant being along the way.

5.2.3.2 Ship

The wool top is shipped between a South Island port and Shanghai in China a distance of 5,650 nautical miles or 10,460 km (www.chinaports.com.cn). The wool is spun in China.

A review of shipping fuel use, by Saunders et al. (2005), found that energy and emission coefficients for sea transport did show general consistency with one or two exceptions. The figure used in this report is 0.12 MJ/tonne-km. This has been calculated from shipping having carbon dioxide emissions of 0.007 $kgCO_2$/t-km (Department for Transport, 2003), and the carbon content of diesel being 2.68 $kgCO_2$/ℓ (Defra www.defra.gov.uk/environment/business/envrp/gas/05.htm). Dividing the shipping emissions by the carbon content per litre of diesel equals 0.0026 ℓ/t-km. Multiplying this figure by the primary energy content of New Zealand diesel (44.3 MJ/ℓ), given that the ships refill in New Zealand, gives a rate of 0.12 MJ/t-km.

This is higher than the 0.09 MJ/tonne-km reported by the Commonwealth Government (2001) but lower than the 0.2 MJ/tonne-km used by Wells (1998), and the similar amount reported in Schilperoord (2004). Webb (2004) states that bulk shipping uses 0.2 MJ/tonne-km, while BIMCO (2001) state that: "a fairly fast ship carrying around 25,000 tonnes of cargo at 18.5 knots uses only 0.12 mega joules per tonne-kilometre".

5.2.4 Wool Processing

Wool processing includes sorting and blending, scouring and top making. The wool top is then shipped to China prior to spinning.

Different wool types are usually blended at the scourer. Different hoppers are used for each wool type, which are automatically fed into the system at a specified percentage.

Scouring occurs through a series of bowls. The first two bowls are usually hot water where, with the help of detergent, suint and grease are removed. The grease is extracted and turned into lanolin.

The material flows through a wool scourer are described in Table 10.

Table 10 Distribution of Material in Wool Scouring

	Present in greasy wool	Added during scouring	Removed in cream	Removed in settling pit	Effluent discharge
Fibre	55				
Grease	14		5.6	0.3	8.1
Suint	5		0.1	0.3	4.6
Dirt	15			3.0	12.0
Water	11	1,000.0	8.2	100.0	903.0
Detergent and Builder		2.5	0.1	0.1	2.3

All figures are percentage of greasy wool weight
Source: Wood, 1983.

The percentage of clean wool in the 'greasy wool weight' after grease, suint and dirt have been removed is 66% (Wood, 1983). The Farm Technical Manual (Fleming, 2003) has a slightly higher yield of 70%.

The yield of clean dry fibre that goes from the wool scourer into the top making stage is 55% (66% minus 11% water).

Inputs during wool scouring were allocated on the basis of a 55% clean dry fibre yield and the grease by-product being 5.9%. Inputs were allocated to these two outputs on the basis of weight, being 90% to wool and 10% to grease.

In the top making stage there is a 91% yield. By-products include 6.5% wool noils and 1.3% dirt and manure which is sold to fertiliser manufacturers. Just 1.3% of the input is disposed of as clean waste. Table 11 shows the product flows.

While half of the dirt and manure is sold to fertiliser manufacturers it was decided that no energy would be allocated to this output. This agrees with the methodology used by Barber (2004b) where the raw material for compost had a zero energy value, given that it usually comes from a waste stream, plus a little energy (0.27 MJ/kg compost) for transporting and turning.

Table 11 Distribution of Material in Wool Top Making

	Present in scoured wool	Removed as a by-product	Waste discharge
Fibre	91.0		
Carding			
Noils	0.7	0.7	
Dirt, manure & vegetable matter	1.1	0.5†	0.5
Combing			
Noils	5.8	5.8	
Dirt, manure & vegetable matter	1.4	0.7†	0.7
Total	**100.0**	**7.7**	**1.3**

All figures are percentage of scoured wool weight
Source: Pers. comm. O'Brien, Chargeurs Wool (NZ) Ltd, 2005
† No energy was allocated to this by-product

5.3 Carbon Dioxide Emissions

5.3.1 Carbon Dioxide Emissions from Direct Energy Inputs

Carbon dioxide is released during the burning process of fossil fuels. These emissions are primarily dependent on the carbon content of the fuel. Due to the molecular weight ratio of carbon dioxide to carbon (44:12), multiplying the weight of carbon by 3.6667 gives the quantity of carbon dioxide emitted. Carbon dioxide emissions from New Zealand diesel and petrol are 68.7 and 66.6 gCO_2/MJ respectively (Baines, 1993). It was assumed that all fugitive emissions from liquid fuels were diesel, which slightly alters the petrol emissions on a primary energy basis. The emission rates are shown in Table 12.

New Zealand's electricity is dominated by hydro-electric generation. In 2003 59% of electricity was generated from renewable energy sources, this improved in 2004 to 64%. The most recent electricity carbon emission data is for 2003, which was a drier than normal year, and consequently carbon emissions were higher than normal. Of the 6.38 million tonnes emitted for electricity generation in 2003 (Brown and Petrie, 2005) natural gas accounted for 56% and coal 44%.

Table 12 Carbon Dioxide Emissions Rates of Direct Energy Inputs

Description	**CO_2 (g CO_2/MJ of Primary Energy)**
Diesel	68.7 [a]
Petrol	67.0 [a]
Electricity	21.7 [b + c]

Source:
[a] Baines (1993). Adjusted to include a component of diesel fugitive emissions
[b] MED (2005)
[c] Brown and Petrie (2005)

5.3.2 Carbon Dioxide Emissions from Indirect Energy Inputs

Carbon dioxide is released during the mining, processing and transport of fertiliser, agrichemicals and purchased feed.

Like the energy coefficients (Table 7) the total carbon dioxide emission for fertiliser has been based on five key elements; N, P, K, S and Mg; plus lime. The data presented by Wells (2001) is used to estimate the carbon dioxide emissions from fertiliser and lime and are shown in Table 13 below. Over 90% of the carbon dioxide emissions from lime occur on reaction with the soil.

Agrichemical carbon dioxide emissions are based on a rate of 0.06 kgCO_2/MJ (Wells, 2001). This is derived from a combination of fuels used in the production process including diesel at 0.07 kgCO_2/MJ, gas at 0.05 kgCO_2/MJ and electricity at 0.02 kgCO_2/MJ.

Carbon dioxide emissions from purchased feed in the form of silage and hay are based on 0.058 kgCO_2/MJ (Wells, 2001). Grain emissions are 0.122 kgCO_2/kg which is equal to 0.044 kgCO_2/MJ. This is based on findings by Barber (2004a) and has been adjusted to exclude the minor contribution from capital equipment in order to remain consistent with the methodology used in this study.

Table 13 Carbon Dioxide Emissions from Mining, Manufacturing, Packaging and Distribution of Indirect Inputs

	CO_2 ($kgCO_2$/kg or ai)	CO_2 ($kgCO_2$/MJ)
Fertiliser		
Nitrogen (N)	3.0	0.05
Phosphorus (P)	0.9	0.06
Potassium (K)	0.6	0.06
Sulphur (S)	0.3	0.06
Magnesium (Mg)	0.3	0.06
Lime	0.4	0.72
Agrichemical		
Animal remedies	12.6	0.06
Herbicide	18.6	0.06
Insecticide	17.7	0.06
Fungicide	12.6	0.06
Other	12.6	0.06
Purchased Feed		
Grain (barley)	0.122	0.04
Silage	0.087	0.06
Hay	0.087	0.06

6.0 LIFE CYCLE INVENTORY

6.1 Farm Description

Tables 14, 15 and 16 are a summary of the average farm in each category and the overall average of the 24 surveyed farms. The three farm categories are strikingly different in all aspects of their operations, except for the percentage of sales. See Section 5.1.1 for a description of how the farm categories were determined.

Table 14 Average Farm Area

Farm Category	Number of Farms	Total Area (ha)	Effective Area (ha)	Irrigated Area	Cash Crop Area
Extensive	8	16,184	14,023	47.0	0.0
Medium Intensive	8	7,808	7,422	45.5	0.0
Intensive	8	935	850	95.5	3.7
Survey Average	**24**	**8,309**	**7,432**	**62.7**	**1.2**

Table 15 Average Farm Stock

Farm Category	Average Stock Units	Average Sheep Stock Units	Average s.u./ha
Extensive	13,013	10,089	0.9
Medium Intensive	17,352	12,534	2.6
Intensive	5,116	4,339	7.4
Survey Average	**11,827**	**8,987**	**3.7**

Table 16 Average Farm Production Intensity

Farm Category	Net Stock Sales (kg/ha)		Wool (kg/ha)	Cash Crop (kg/ha)	Percentage of Sales by Weight		
	Live Weight	Carcass Weight			Carcass Weight	Wool	Cash Crop
Extensive	16.9	8.3	3.6	0.0	70%	30%	0%
Medium Intensive	56.4	27.7	9.6	0.0	74%	26%	0%
Intensive	178.3	83.9	31.9	34.6	64%	24%	12%
Survey Average	**83.9**	**40.0**	**15.0**	**11.5**	**69%**	**27%**	**4%**

6.2 Resource Inputs

Resource inputs include direct and indirect energy. These are presented based on the main functional unit, per tonne of wool top, in addition to all on-farm inputs are described on a per hectare, per stock unit, and per tonne of greasy wool basis.

6.2.1 On-Farm

Table 17 presents the average inventory of resource inputs for the 24 merino farms surveyed. Appendix 2 shows the resource inputs for each of the three farm categories.

Fertiliser is often the most significant on-farm energy input; however in this case liquid fuels are higher, at 40% of the total on-farm energy cost, followed closely by fertiliser at 39%. Unlike many other agricultural systems where nitrogen dominates, with its high use and high energy cost to manufacture, on these merino farms there is largely an even split of embodied energy between nitrogen, phosphorus and sulphur. The exception to this are the intensive operations that show the more typical nitrogen domination.

Table 17 Average Resource Inputs and Production

	Unit	Quantity			
		per hectare	**per s.u.**	**per tonne greasy wool**	**per tonne wool top**
Direct Energy Inputs					
Diesel	ℓ	2.7	0.8	51.8	87.0
Petrol	ℓ	1.0	0.3	18.2	30.6
Contractors (diesel)	ℓ	3.2	0.8	52.1	87.6
Electricity	kWh	24.7	4.7	285.8	480.2
Indirect Energy Inputs (Consumables)					
Nitrogen	kg	2.1	0.6	30.1	50.5
Phosphorous	kg	4.4	1.4	102.0	171.4
Potassium	kg	0.1	0.0	1.4	2.4
Sulphur	kg	10.6	3.7	271.0	455.3
Magnesium	kg	0.1	0.0	0.9	1.6
Lime	kg	44.8	11.2	614.4	1,032.5
Fertiliser	kg	62.1	16.9	1,019.9	1,713.7
Agrichemicals	kg ai	0.08	0.02	1.48	2.5
Purchased Feed	kg DM	9.1	2.5	168.1	282.5
Production					
Total Farm Production †	kg	66.6	15.3		
Wool	kg	15.0	3.9‡		
Carry Capacity	s.u.	3.7			

† Total Production includes the sale of meat carcass, cash crops and wool
‡ Production of wool per sheep stock unit was 5.6 kg

Lime is the most variable of all the inputs with just 7 of the 24 farms recording applications. While this has little impact on the total energy use it does cause a significant amount of uncertainty in the carbon dioxide indicator. A description of lime applications is given in Table 18.

Table 18 Application of Lime

Farm Category	Number of farms that applied lime	Lime	
		kg/ha	kg/tonne farm output
Extensive	1	1.9	163
Medium Intensive	4	36.2	968
Intensive	2	96.3	713
Average		**44.8**	**614**

6.2.2 Processing

Table 19 presents the resource inputs in wool scouring and top making. The wool and by-product output from wool scouring is based on the findings of Wood (1983) as is the quantity of detergent used. It was assumed that all energy use was electricity, although this would vary between different processing plants.

Total processing energy use was based on BWK's 1998 energy use data (BWK, 1999). BWK is a German wool processing plant that undertakes wool scouring and top making. Eighty percent of their production is wool with the rest being man-made fibres. In 1998 they had output of 49,481 tonnes of wool top and man-made fibres. The environmental report does not disaggregate the wool and man-made fibres.

Primary energy use by BWK in 1998 was 354,400 GWh, which based on their total output of wool and man-made fibre products is 25.8 MJ/kg. Using New Zealand's electricity energy coefficient of 7.34 MJ/kWh and allocating a proportion of energy to the by-products of grease and wool noils, based on weight, total energy use for wool processing in New Zealand is estimated to be 3.0 kWh/kg or 21.7 MJ/kg.

Energy used in top making was taken from one New Zealand operation (O'Brien, 2005).

Table 19 summarises the resource inputs in wool processing.

Table 19 Resource Inputs into Wool Processing

	Wool output (kg/t greasy)	By -products (kg/t greasy)	Electricity		Detergents	
			(kWh/t greasy)	(kWh/t top)	(kg ai/t greasy)	(kg ai/t top)
Wool scouring	550	59	1,552	2,607	13	21
Top making	501	36	208	349	-	-
Total processing	**501**	**95**	**1,759**	**2,956**	**13**	**21**

6.2.3 Transport

Transport included moving greasy wool from the farm to port. It was assumed that the wool scouring and top making were close to the port, so the transport of processed wool from the processor to the port had already been accounted for. Shipping the processed wool from the Dunedin port to Shanghai in China is included in transport. These resource inputs are summarised in Table 20 below.

Average diesel use for the transport of greasy wool between farm and port was 3.7 ℓ/t greasy wool. Extensive farms were the furthest from the port and used 4.7 ℓ/t followed by medium intensive farms at 3.8 ℓ/t, with the intensive operations being the closest and using just 2.4 ℓ/t greasy wool.

The shipping of processed wool the 5,650 nautical miles to China used 27.3 ℓ/t wool top.

Table 20 Resource Inputs in Transport

	Unit	**Quantity (per tonne wool top)**
Cartage to port	ℓ	6.1
Shipping to China	ℓ	27.3

6.3 Emissions

The emission assessed in this study is carbon dioxide

Table 21 Emissions from Farm to Top Making

	Carbon dioxide	
	(kg/t greasy)	**(kg/t top)**
On-farm		
Direct [a]	414	696
Indirect [b]	571	960
Processing		
Direct [c]	280	471
Indirect [d]	0	0
Transport		
truck	11	19
ship	50	84
TOTAL	**1,326**	**2,230**

[a] includes diesel, petrol and electricity
[b] includes fertiliser, agrichemicals and supplementary feed
[c] electricity
[d] detergents

7.0 LIFE CYCLE IMPACT ASSESSMENT

Life cycle impact assessments evaluate resource use and emissions based on the life cycle inventory.

The impact category studied was total energy use. Carbon dioxide emissions were also determined as they are very closely linked to energy use.

7.1 Total Energy Use

7.1.1 On-Farm

Table 22 illustrates the average energy used by the 24 merino farms surveyed. Table 23 shows energy use specific to each of the three different farm categories.

Table 22 Total Energy Use

	Total Energy Input (MJ)			
	per hectare	**per s.u.**	**per tonne greasy wool**	**per tonne wool fibre**
Direct Energy Inputs				
Diesel	118.7	34.8	2,295	3,856
Petrol	40.3	11.6	729	1,225
Contractors (diesel)	140.9	35.0	2,310	3,882
Electricity	181.6	34.3	2,097	3,524
Sub-total	**481.5**	**115.7**	**7,431**	**12,487**
Indirect Energy Use				
Nitrogen	134.1	36.1	1,955	3,285
Phosphorous	65.4	21.1	1,530	2,571
Potassium	0.8	0.2	14	24
Sulphur	53.2	18.6	1,355	2,277
Magnesium	0.5	0.1	5	8
Lime	26.9	6.7	369	619
Fertiliser	280.8	82.8	5,227	8,783
Agrichemicals	23.4	7.0	444	747
Purchased Feed	18.1	4.7	315	529
Sub-total	**322.3**	**94.4**	**5,987**	**10,059**
TOTAL	**803.8**	**210.1**	**13,418**	**22,546**

Figure 3 Total Energy Use per Tonne of Output

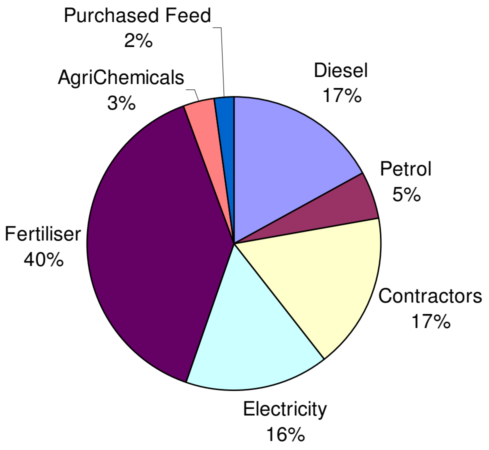
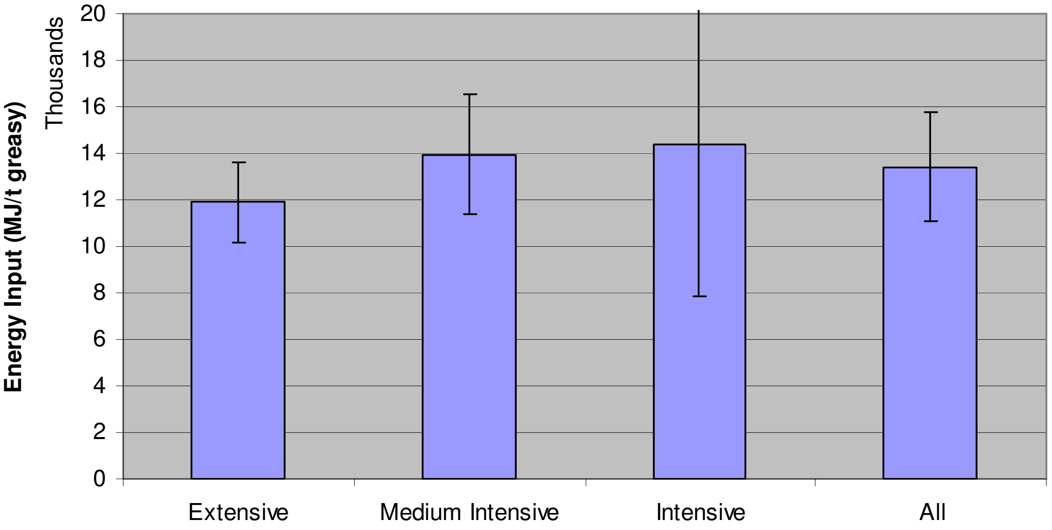


Table 23 Total Energy Use by Farm Category

Farm Category	Total Energy Input (MJ)			
	per hectare	per s.u.	per tonne greasy wool	per tonne wool top
Extensive	145	155	11,890	19,980
Medium Intensive	510	200	13,940	23,425
Intensive	1,755	270	14,425	24,235
Average	**805**	**210**	**13,420**	**22,545**

None of the farm categories were significantly different at the 5% level. Average total energy use for all farms was 13,420 MJ/t greasy wool (22,545 MJ/t top), with the 95% confidence interval being ± 2,360 (± 3,960 for wool top) and the individual farms ranged between 6,030 MJ/t greasy wool (10,140 MJ/t top) and 34,740 MJ/t greasy wool (58,375 MJ/t top), see Figure 4. The median was 12,230 MJ/t greasy wool (20,545 MJ/t top).

Figure 4 Total Energy Input per Tonne Greasy Wool



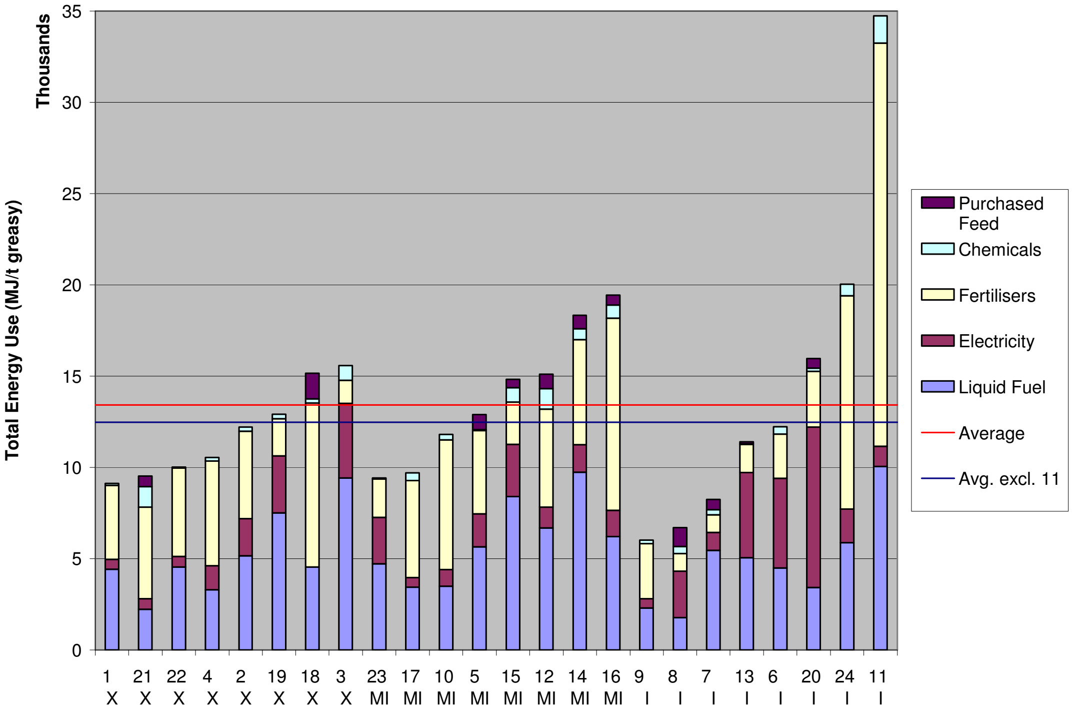
The error bars are the 95% confidence interval for the mean

On-farm the single largest energy user was liquid fuel at 20%, slightly greater than the embodied energy in fertiliser at 19%. There was little variation in these proportions between the different farm types, with liquid fuels ranging between 17 and 22% and fertiliser between 18 and 21%. Average electricity use was 8% but was up to 11% for the intensive farms, due to irrigation, and was 6% for both extensive and medium intensive farms. For one intensive farm (Farm 20) electricity use was 55% of their total on-farm energy use and 30% of total life cycle energy use.

One of the most noticeable aspects illustrated in Figure 5 is the very high fertiliser use on Farm 11. This was the second smallest farm (280 ha) with an average nitrogen application rate of 22 kgN/ha. This rate is ten times the average and more than double the next highest rate. While Farm 11 has been included in the overall analysis, it could reasonably have been excluded on the basis that sheep made up just 23% of their stock numbers compared to an average on the other 23 farms of 79% (ranging between 47% and 100%).

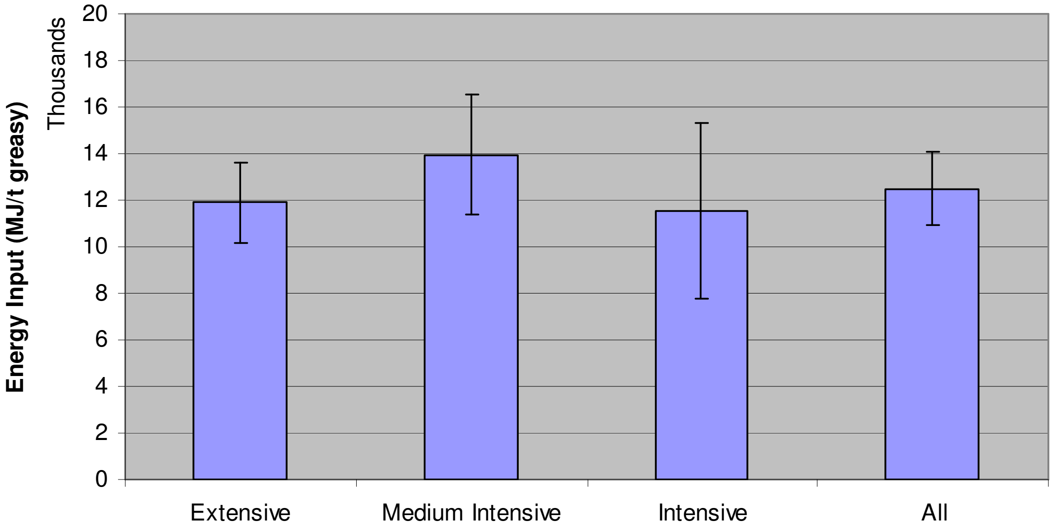
Figure 6 shows the effect of removing Farm 11 as an outlier. Energy use on the intensive category of farms is reduced from 14,425 MJ/t greasy (24,235 MJ/t top) down to 11,520 MJ/t greasy (19,360 MJ/t top). Farm 11 accounts for 40% of the variability in this farm category. Average total energy use of all farms is reduced by 7% from 13,420 MJ/t greasy (22,550 MJ/t top) to 12,490 MJ/t greasy (20,990 MJ/t top). Farm 11 has been included in all other results.

Figure 5 Individual Farm Total Energy Use per Tonne Top



Note: X = extensive farm type
MI = medium intensive
I = intensive

Figure 6 Total Energy Input per Tonne Greasy Wool – Excluding Farm 11



7.1.2 Processing and Transport

Total energy use in the processing and transport of wool top is presented in Table 24.

Table 24 Total Energy Use in Wool Processing and Transport

	Energy (MJ/t top)
Cartage to port	273
Processing	21,698
Detergents	4
Shipping to China	1,212
TOTAL	**23,186**

7.1.3 Wool Life Cycle

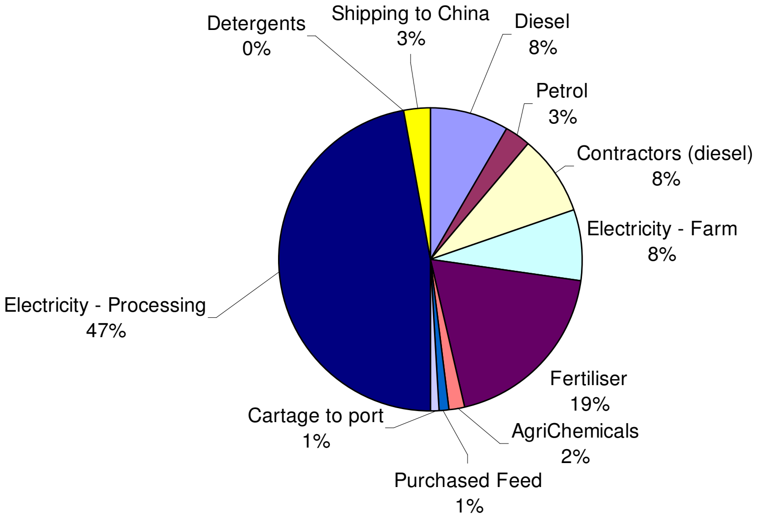
Total energy use from a New Zealand sheep farm to a spinning mill in Shanghai China is 45,730 MJ/t top (Table 25). Just under half (49%) of total energy use occurs on-farm.

Table 25 Wool Top - Total Energy Use from Farm to China

	Total Energy (MJ per tonne wool top)
On-Farm	
Direct Energy Inputs	*12,490*
Indirect Energy Inputs	*10,060*
Sub-total	**22,550**
Processing	**21,700**
Transport	**1,490**
TOTAL	**45,730**

As can be seen in Figure 7, energy used for wool processing, almost 90% of which is consumed during wool scouring, was the single largest energy user. This is also the input for which there is the least certainty. The figure for processing energy use was adapted from BWK (1999) data. BTTG (1999) estimated energy use was 60% lower than this and three years later BWK (2002) estimated energy use was 24% higher.

Figure 7 Distribution of Total Energy Use in the Wool Life Cycle



7.2 Carbon Dioxide Emissions

7.2.1 On-Farm

Table 26 shows the average carbon dioxide emissions from the 24 merino farms surveyed. Table 27 shows total carbon dioxide emissions for each farm category.

Table 26 Total Farm Carbon Dioxide Emissions

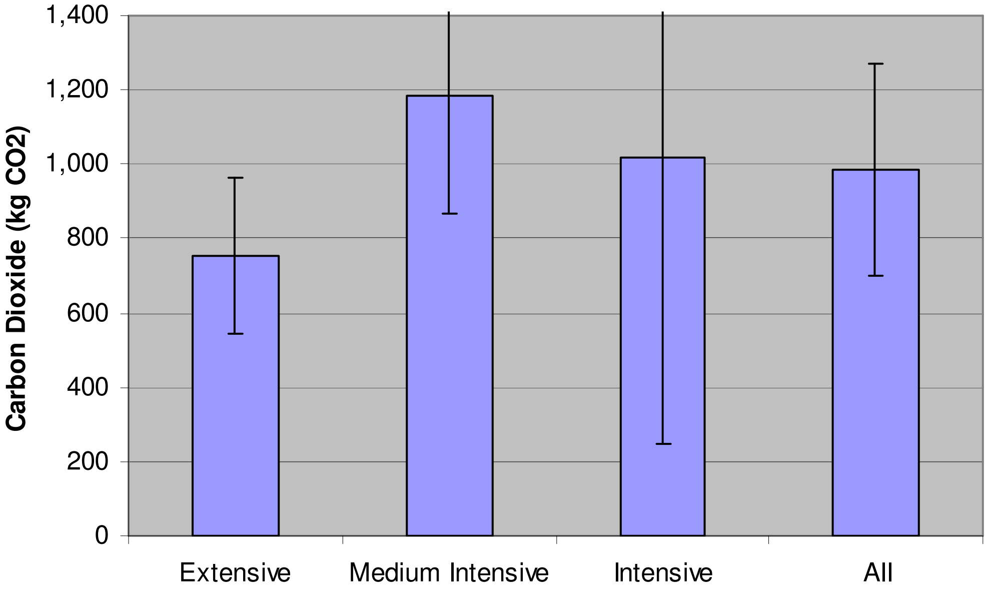
	Total Carbon Dioxide Emissions (kg CO_2)			
	per hectare	per s.u.	per tonne greasy wool	per tonne wool top
Direct Energy Inputs				
Diesel	8.3	2.4	159	268
Petrol	2.7	0.8	49	82
Contractors (diesel)	9.8	2.4	161	270
Electricity	3.9	0.7	46	76
Sub-total	**24.7**	**6.4**	**414**	**696**
Indirect Energy Use				
Nitrogen	6.2	1.7	90	152
Phosphorous	3.9	1.3	92	154
Potassium	0.0	0.0	1	1
Sulphur	3.2	1.1	81	137
Magnesium	0.0	0.0	0	0
Lime	19.4	4.9	265	446
Fertiliser	32.7	8.9	530	890
Agrichemicals	1.4	0.4	27	45
Purchased Feed	0.8	0.2	15	24
Sub-total	**34.9**	**9.5**	**571**	**960**
TOTAL	**59.6**	**15.9**	**985**	**1,655**

Table 27 Total Carbon Dioxide Emissions by Farm Category

Farm Category	Total Carbon Dioxide Emissions (kg CO_2)			
	per hectare	per s.u.	per tonne greasy wool	per tonne wool top
Extensive	9.1	9.9	750	1,265
Medium Intensive	43.9	17.4	1,185	1,990
Intensive	125.8	20.4	1,020	1,710
Average	**59.6**	**15.9**	**985**	**1,655**

None of the farm categories were significantly different at the 5% level. Average total carbon dioxide emissions for all 24 farms were 985 kg CO_2/t greasy wool (1,655 kg CO_2/t top) with the 95% confidence interval being ± 285. Carbon dioxide emissions from individual farms ranged between 305 and 3,705 kg CO_2/t greasy wool (both were intensive farms). The median was 730 kg CO_2/t greasy wool (1,225 kg CO_2/t top).

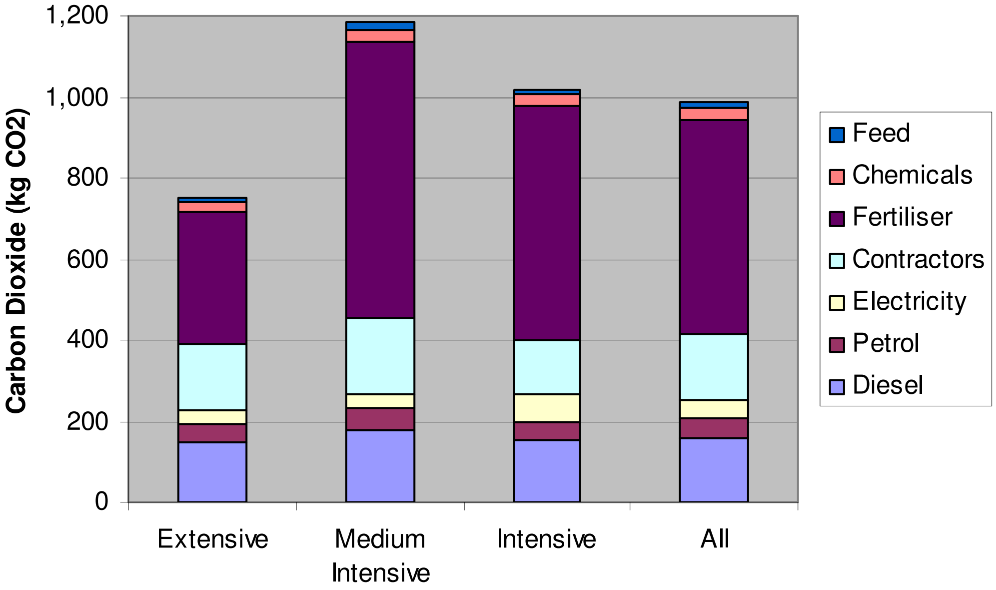
Figure 8 **Total Carbon Dioxide Emissions per Tonne Greasy Wool**



The error bars are the 95% confidence interval for the mean

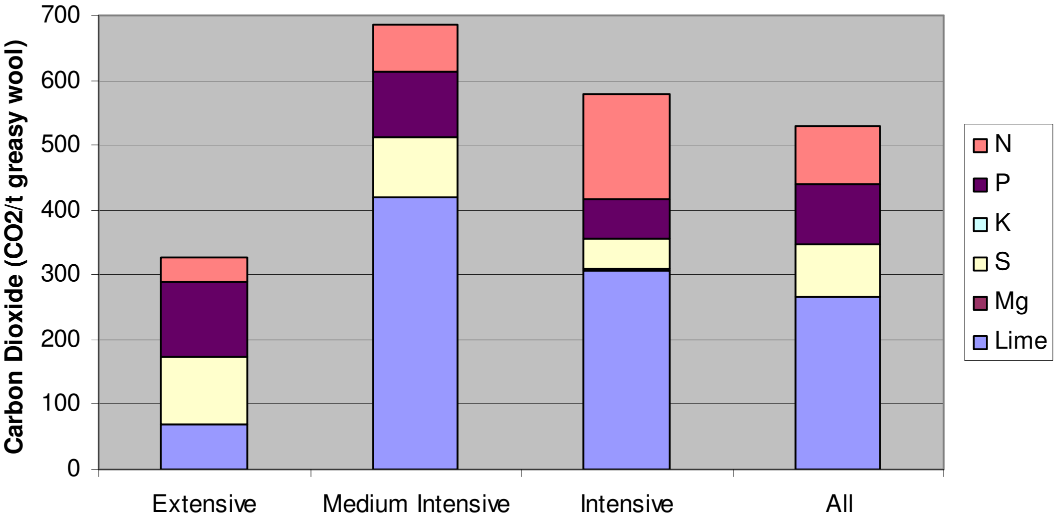
Figure 9 shows the contribution of each farm input, with the single largest contribution coming from fertiliser.

Figure 9 **Source of Carbon Dioxide Emissions per Tonne Greasy Wool**



Of the fertiliser applied, lime is the single largest contributor (Figure 10), accounting for 50% of farm CO_2 emissions from fertiliser and 27% of total farm CO_2 emissions. On a per tonne of wool basis medium intensive farms are the largest users of lime, where it accounts for 61% of CO_2 emissions from fertiliser and 35% of total farm CO_2 emissions. By contrast lime is only a minor energy input at 2.8% of total energy.

Figure 10 Fertiliser Carbon Dioxide Emissions per Tonne Greasy Wool



7.2.2 Processing and Transport

Table 28 shows the carbon dioxide emissions of transport to the port, wool processing, and shipping to China. It was assumed that the energy source for all wool processing was electricity. This underestimates emissions where other energy sources may be used, like gas and coal powered boilers. If 75% of the processing energy was gas or coal, rather than all electricity, then CO_2 emissions rise from 470 kg CO_2/t top to 970 and 1,540 kg CO_2/t top respectively.

Table 28 Total Processing and Transport Carbon Dioxide Emissions

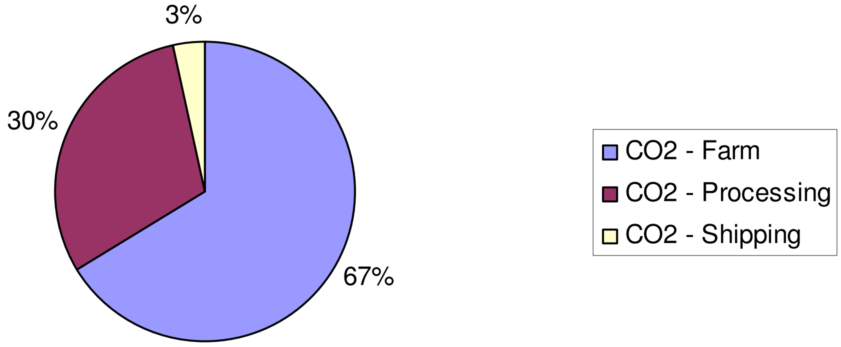
	Carbon Dioxide (kg CO_2/t top)
Cartage to port	19
Processing †	471
Detergents	0
Shipping to China	84
TOTAL	**574**

† assumes an electricity energy source

7.2.3 Wool Life Cycle

On-farm activities account for two thirds of wool's carbon dioxide emissions. As shown in section 7.2.1.1, more than a quarter of these on-farm emissions (18% overall) are from the application of lime and its reaction with the soil.

Figure 11 Distribution of CO_2 Emissions in the Wool Life Cycle



8.0 CONCLUSIONS

Life Cycle Assessment (LCA) has become an important tool for measuring the impact that a product has on the environment, from the extraction of raw materials, through the production process and final product use, disposal or recycling. This study involved a literature search on textile LCAs and conducted a simplified LCA of New Zealand merino wool to determine total energy use and carbon dioxide emissions from on-farm production of wool through to the processed wool tops being delivered to a spinning factory in China.

LCA methodology has evolved largely from total energy use studies. To date most of the work conducted on textiles reflects this history with an emphasis on total energy. While most of the literature lacks well described system boundaries and detailed inventories, which would allow the total energy use results to be checked, they do nevertheless provide a good guide as to the magnitude of energy use in the production of textiles.

This report found that wool production had a total energy use of 46 MJ/kg wool tops, half of which occurs on farm. On-farm energy use is 23 MJ/kg wool tops (13 MJ/kg greasy wool). Wool processing accounts for 47% of total energy use, of which almost 90% occurs during wool scouring. The wool processing data is the area with which the least confidence is associated, due to the difficulty of finding suitable literature and industry data. It is also understood that there is considerable variation in energy use between different processing plants.

Uncertainties, numerous assumptions, and vested interests in Life Cycle Assessments create scepticism about the results, particularly when products are compared. ISO standards recommend that when comparing products a sensitivity and uncertainty analysis be conducted. This however is only possible when there is a complete set of raw data for each product, which is not the case in this study.

While most LCA practitioners, including the European Environmental Agency, recommend that results are not used to claim that one product is more environmentally friendly than another, it is possible to claim that given a specified set of criteria, for example total energy use, that one product performs better than another. Caution is needed and it is extremely important not to over-claim. The studies should also be peer reviewed.

Given these caveats and acknowledging that this study has not been peer reviewed, it was found that the production of polyester fibre used 2.7 times more energy than wool. Acrylic, the fibre that most resembles wool, used 3.8 times as much energy in its production and nylon required over 5 times the energy required to produce wool.

This project has not calculated a single score LCA due to the limited number of categories investigated but, more importantly, because this often hides the results behind the normalisation of the data (transforms an indicator by dividing it by a selected reference value) and weightings (based on value choices). Currently there is not a New Zealand specific methodology for normalisation and weightings, although one is under development (Nebel, 2005).

This project has provided a significant advance in the understanding of resource inputs in New Zealand sheep and beef farms and in particular the total energy use for the production of merino wool. Areas that need investigating in the future include further utilisation of existing data and the collection of additional data as described below.

Using the existing data:

- Conducting a sensitivity analysis;
- Determining the environmental hotspots through a contribution analysis;
- Analysing the data in an LCA software package like GaBi or SimaPro, and;
- Expanding the number of impact categories to include acidification and nitrification (although this will be dependent on reference values for nitrate leaching).

Collecting additional data:

- Determining a national average energy use for wool that weights the findings based on sheep and beef farm classes (the current study uses an average of the 24 surveyed farms);
- Investigating other wool and farm classes;
- Investigating wool processing in more detail;
- Progressing the LCA beyond top making to include spinning, dying, apparel manufacture, customer use, and disposal;
- Adding capital items (tractors, fences, races etc), and;
- Conducting a sensitivity analysis on the effect of changing the allocation rules from a weight to financial basis.

Findings from current longer term research and development, such as the major ARGOS (Agriculture Research Group on Sustainability) and Ecological Footprint Plus (Canesis) projects should, in due course, assist in further developing LCA approaches for all wool products, including merino wool. Meanwhile, the results from this study provide an initial quantification of energy impacts that will help the merino industry understand its position relative to other fibres.

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Appendix 1 Detailed Description of Textile Industry Energy Use

Fibre Type	Scope	Energy Use per Unit	Unit	Energy Use MJ/kg	Source
Nylon	Production including the feedstock	4.7 – 5.8	toe / tonne	222	Wiseman, 1981
	Production including the feedstock	250 – 270	GJ / tonne	260	BTTG, 1999
	Production			148	AIA, 1992
	Production including the feedstock			262	GaBi database
	Texturing, winding, warping and knitting	60 - 65	GJ / tonne	63	BTTG, 1999
Acrylic	Production including the feedstock	3.7 – 6.9 avg. = 4.0 excluding high value of 6.9	toe / tonne	165	Wiseman, 1981
	Production including the feedstock			157	Laursen et al., 1997
	Production of Polymethyl methacrylate (PMMA), granulate			194	GaBi database
Polyester	Production including the feedstock	2.6 – 3.9	Tonnes oil equivalent (toe) / tonne	138	Wiseman, 1981
	PET resin manufacture	4,963	BTU/blouse	97	Franklin Associates, 1993
	PET fibre manufacture	742	BTU/blouse	15	Franklin Associates, 1993
	Fabric manufacture	4,441	BTU/blouse	87	Franklin Associates, 1993
	Production of polyester filament	100 – 120	GJ / tonne filament	110	BTTG, 1999
	Production – Europe			104	Cherrett et al., 2005
	Production – USA			127	Cherrett et al., 2005

Fibre Type	**Scope**	**Energy Use per Unit**	**Unit**	**Energy Use MJ/kg**	**Source**
	Polyester (PET) production			148	GaBi database
Polypropylene	Production including the feedstock	2.8	toe / tonne	117	Wiseman, 1981
Viscose	Wood pulp to fibre production	1.8 – 2.8	toe / tonne	100	Wiseman, 1981
	Processing plus production of raw materials			71	Firth (1980) in Laursen et al., 1997
	Wood production to pulp			26	Firth (1980) in Laursen et al., 1997
	Wood production for 1 kg viscose fibre			36	MoDo, 1995
	Wood pulp to fibre production	68 - 96	MJ/kg	82	Woodings, 1993
Cotton	Production to ginning	0.7	toe / tonne	29	Wiseman, 1981
	Production to ginning			49	van Winkle (1978) in Laursen et al., 1997
	Fibre production total			60	Kalliala and Nousiainen, 1999
	Organic fibre production			54	Kalliala and Nousiainen, 1999
	Crop cultivation and fibre production - USA			26	Cherrett et al., 2005
Wool	Production including the feedstock	0.9	toe / tonne	38	Wiseman, 1981
	Production of greasy	1,000	MJ/ha	8	Nguyen, in Laursen et al., 1997
	Scouring, drying and combing	15	GJ / tonne fibre	15	BTTG, 1999
	Scouring, drying and combing	21 - 29	MJ/kg input	26 - 34	BWK, 1999 and 2002

Appendix 2 Resource Inputs by Farm Type

Resource Inputs and Production – Farm Type Extensive

	Unit	Quantity			
		per hectare	per s.u.	per tonne greasy wool	per tonne wool top
Direct Energy Inputs					
Diesel	ℓ	0.6	0.7	48.8	82.0
Petrol	ℓ	0.2	0.2	16.3	27.3
Contractors (diesel)	ℓ	0.7	0.7	52.5	88.2
Electricity	kWh	2.8	2.9	209.1	351.3
Nitrogen	kg	0.1	0.2	13.4	22.4
Phosphorous	kg	1.4	1.6	125.8	211.4
Potassium	kg	0.0	0.0	2.3	3.8
Sulphur	kg	4.0	4.3	342.3	575.2
Magnesium	kg	0.0	0.0	0.8	1.4
Lime	kg	1.9	2.3	163.0	273.8
Fertiliser	kg	7.6	8.4	647.5	1,088.0
Agrichemicals	kg ai	0.02	0.02	1.26	2.1
Purchased Feed	kg DM	1.8	2.2	160.1	268.9
Production					
Total Farm Production †	kg	11.9	12.9		
Wool	kg	3.6	3.9 ‡		
Carry Capacity	s.u.	0.9			

† Total Farm Production includes the sale of meat carcass, cash crops and wool

‡ Production of wool per sheep stock unit was 5.0 kg

Appendix 2 cont. Resource Inputs by Farm Type

Resource Inputs and Production – Farm Type Medium Intensive

	Unit	Quantity			
		per hectare	per s.u.	per tonne greasy wool	per tonne wool top
Direct Energy Inputs					
Diesel	ℓ	1.9	0.8	57.2	96.1
Petrol	ℓ	0.8	0.3	21.1	35.5
Contractors (diesel)	ℓ	2.3	0.8	60.1	100.9
Electricity	kWh	7.8	3.1	216.9	364.4
Nitrogen	kg	0.8	0.4	23.7	39.8
Phosphorous	kg	4.3	1.6	113.2	190.3
Potassium	kg	0.0	0.0	0.8	1.3
Sulphur	kg	12.1	4.4	310.4	521.5
Magnesium	kg	0.0	0.0	0.0	0.0
Lime	kg	36.2	14.7	967.9	1,626.3
Fertiliser	kg	53.4	21.1	1,415.9	2,379.2
Agrichemicals	kg ai	0.06	0.02	1.68	2.8
Purchased Feed	kg DM	7.5	2.8	206.0	346.2
Production					
Total Farm Production †	kg	37.3	14.4		
Wool	kg	9.6	3.7 ‡		
Carry Capacity	s.u.	2.6			

† Total Farm Production includes the sale of meat carcass, cash crops and wool

‡ Production of wool per sheep stock unit was 5.1 kg

Appendix 2 cont. Resource Inputs by Farm Type

Resource Inputs and Production – Farm Type Intensive

	Unit	Quantity			
		per hectare	per s.u.	per tonne greasy wool	per tonne wool top
Direct Energy Inputs					
Diesel	ℓ	5.5	0.9	49.2	82.7
Petrol	ℓ	2.0	0.3	17.2	29.0
Contractors (diesel)	ℓ	6.6	0.8	43.7	73.5
Electricity	kWh	63.7	8.1	431.3	724.7
Nitrogen	kg	5.2	1.1	53.2	89.4
Phosphorous	kg	7.4	1.0	67.0	112.5
Potassium	kg	0.2	0.0	1.2	2.0
Sulphur	kg	15.8	2.5	160.3	269.4
Magnesium	kg	0.3	0.0	2.0	3.3
Lime	kg	96.3	16.7	712.5	1,197.3
Fertiliser	kg	125.1	21.4	996.2	1,673.9
Agrichemicals	kg ai	0.16	0.03	1.50	2.5
Purchased Feed	kg DM	17.9	2.4	138.3	232.3
Production					
Total Farm Production †	kg	150.4	18.7		
Wool	kg	31.9	4.2 ‡		
Carry Capacity	s.u.	7.4			

† Total Farm Production includes the sale of meat carcass, cash crops and wool
‡ Production of wool per sheep stock unit was 6.7 kg