Bangor University

DOCTOR OF PHILOSOPHY

The Life Cycle Assessment and Moisture Sorption Characteristics of Natural Fibre Thermal Insulation Materials

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Award date:
2008

Awarding institution:
Bangor University

The Life Cycle Assessment and Moisture Sorption Characteristics of Natural Fibre Thermal Insulation Materials

A thesis submitted for the degree of Doctor of Philosophy
of Bangor University

By

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March 2008

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Acknowledgements

Firstly I would like to thank my supervisor Prof Callum Hill for his brilliant guidance and advice throughout this work and continued support from afar.

I am extremely grateful to the ESF funding program and also to Mr Gary Newman of Plant Fibre Technology for not only sponsoring this work, but also the invaluable technical and commercial advice throughout.

I would very much like to thank Dr Richard Murphy for allowing me to work on the LCA project and his guidance. I also thank Miss Sheau Tyun Tai, Dr Gareth Davies and Dr Bill Hillier of Imperial College London and Dr Jeremy Tomkinson, Dr John Williams and Dr David Williams of the NNFCC for their input.

Grateful thanks are extended to Jean-Peirre Buisson of Buitex, Christine Armstrong and Mark Lynn of Second Nature and Mike Duckett of Hemcore for supplying data and information.

I am also extremely grateful to Mr John Evans, Dr Simon Curling, Prof. Mark Hughes, Dr James Carpenter and Dr Graham Ormondroyd, Miss Jennet Wade, Mr James Walmsley, Mr Mathew Ling and of course Bob for their friendly advice, providing places to stay and valuable distractions.

Finally I would like to thank My Family and especially my wife Jennifer to whom I dedicate this work, it simply would not have happened with out you.

Abstract

A comparative Life Cycle Assessment (LCA) was performed on two natural fibre thermal insulation products made from hemp and sheep wool and a benchmark mineral wool product. The assessment revealed both advantages and some disadvantages with the natural fibre materials. A major finding was the particularly low or absent impact in terms of global warming potential shown by the natural fibre materials. This was caused by the renewable carbon sequestered in the material withdrawing carbon dioxide from the atmosphere. With regard to the end of the product life, the study showed that only a proportion of the total amount of carbon dioxide was released in landfilling and composting scenarios.

Dynamic vapour sorption analysis was conducted on varied natural fibres in order to develop a protocol for studying moisture sorption in natural fibres. Data from these studies were subsequently used in calculating the integral heat of wetting in hemp fibres. The energy release caused by the quantity of material studied in the LCA during predicted relative humidity fluctuations was found unlikely to affect the results of the LCA. However, where large quantities of natural fibres are used throughout a construction the heat of wetting may produce a notable difference in the internal temperature of a building and provide a degree of passive environmental control.

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Abbreviations

ADP	Abiotic Depletion Potential
AP	Acidification Potential
BBA	British Board of Agrément
BREEAM	Building Research Establishment Environmental Assessment Method
BSI	British Standards Institution
BUWAL	Bundesamt für Umwelt, Wald und Landschaft (Swiss Agency for the Environment, Forest and Landscape)
BWMB	The British Wool Marketing Board
CEPMC	Council for European Producers of Materials for Construction
CML	The Institute of Environmental Sciences (of Leiden University)
DEFRA	Depertment for Environment, Food and Rural Affairs
DG X1	Environmental Directorate "X1" by the European Commission
DTI	Department of Trade and Industry
DVS	Dynamic Vapour Sorption
EP	Eutrophication Potential
EU	European Union
FAETP	Freshwater Aquatic Eco-Toxicity Potential
FU	Functional Unit
GDP	Gross Domestic Product
GWP	Global Warming Potential
GWP(100)	Global Warming Potential at 100 years
HTP	Human Toxicity Potential
IPCC	Intergovernmental Panel on Climate Change

IPPC	Integrated Pollution Prevention and Control
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory analysis
LCIA	Life Cycle Impact Assessment
LHV	Lower Heating Value (*e.g.* with regard to energy ratings)
M_f	Microfibril (fibre) Saturation Point
MFA	Microfibril Angle
NFI	Natural Fibre Insulation
NBT	Natural Building Technologies
NHx	Nitrogen/Hydrogen compounds (*i.e.* Ammonium or Ammonia)
NNFCC	National Non-Foods Crops Centre
NOx	Nitrogen Oxide compounds
ODP	Ozone layer Depletion Potential
PE	Potential Energy
PLA	Polylactic Acid
POCP	Photochemical Oxidant Creation Potential
PUR	Poylurethane (*e.g.* foam insulation)
Q_f	Heat of Fusion
Q_L	Differential Heat of Wetting
Q_0	Heat of Vaporization
Q_S	Heat of Sublimation
Q_V	Energy required to evaporate one gram of water from the cell wall
REPA	Resource and Environmental Profile Analysis
RH	Relative Humidity

SETAC	Society of Environmental Toxicology and Chemistry
SPOLD	Society for the Promotion of LCA Development
TETP	Terrestrial Eco-Toxicity Potential
UN	United Nations
UNFCCC	United Nations Framework Convention on Climate Change
VOC	Volatile Organic Compound
XPS	Extruded Polystyrene (*e.g.* foam insulation)

1 Introduction

1.1 The Importance of Insulation Materials

"The scientific evidence is now overwhelming: climate change is a serious global threat, and it demands an urgent global response." (Stern, 2006)

Sir Nicholas Stern (2006) assessed a wide range of evidence on the impacts of climate change and on the economic costs, and used a number of different techniques to assess costs and risks to produce the Stern Review: The Economics of Climate Change. From all of these perspectives, the evidence gathered by the review leads to a simple conclusion: the benefits of strong and early action far outweigh the economic costs of not acting.

Based on the evidence gathered it was reported that climate change will affect the basic elements of life for people around the world – access to water, food production, health, and the environment. Hundreds of millions of people could suffer hunger, water shortages and coastal flooding as the world warms. Using the results from formal economic models, the Stern Review estimates that if we don't act, the overall costs and risks of climate change will be equivalent to losing at least 5% of global GDP each year, now and forever. If a wider range of risks and impacts is taken into account, the estimates of damage could rise to 20% of GDP or more. In contrast, the costs of action – reducing greenhouse gas emissions to avoid the worst impacts of climate change – can be limited to around 1% of global GDP each year (Stern, 2006).

Although the Stern Review was generally accepted as a strong message that economic action against the effects of climate change was needed now, it was far from the first of such warnings. At the United Nations Conference on Environment and Development (informally referred to as the Earth Summit), held in Rio de Janeiro in 1992, most countries joined an international treaty, the United Nations Framework Convention on Climate Change (UNFCCC), to begin to consider what can be done to reduce global warming and to cope with whatever temperature increases are inevitable. In 1998, a number of nations including the UK had approved an addition to the treaty: the Kyoto Protocol (UN, 1998), which has more powerful and legally binding measures (UNFCCC, online).

Stemming from the KYOTO protocol The UK Government is committed to cutting its CO_2 emissions by 60% by about 2050 and has a domestic goal of reducing CO_2 emissions by 20% by 2010 (on 1990 levels). In the household sector, the UK Government aims to secure carbon savings of 4.2 Mt of carbon per annum by 2010 (Energy for Sustainable Development Ltd, 2005). According to the former Department for Trade and Industry (DTI, now the Department for Business, Enterprise and Regulatory Reform), the domestic housing sector is responsible for around 28% of total energy use in the UK. Of this, 86 per cent is used for space and water heating (DTI, 2003).

The DTI Energy White Paper published in February 2003 identified energy efficiency as "the cheapest, cleanest and safest way of meeting the UK's overall energy policy objectives" (DEFRA, 2004). If less energy is used, there will be less CO_2 emissions as a result of burning fossil fuels. Insulation is widely accepted and seen as one of the key means of achieving energy efficiency (DTI, 2003).

On recommendation from Energy for Sustainable Development Ltd, the UK government's Department for Environment, Food and Rural Affairs (DEFRA) suggested a corresponding step increase in the number of installations of cavity wall and loft insulation, including top-ups and of un-insulated loft, over the period 2005-2008 (Energy for Sustainable Development Ltd, 2005)

The recent revision to Approved Document Part L: Conservation of Fuel and Power of the Building Regulations, which came into effect in April 2006, was timed to comply with the European Union's Energy Performance of Buildings Directive (EU, 2002) to further improve and raise the energy efficiency standards of building fabric elements in existing, new and refurbished buildings (Potter, 2005). The new regulations are set to increase the average efficiency of new dwellings by 20% by increased insulation and will save up to 1 million tonnes of carbon in the UK per year by 2010 (Energy Efficiency Partnership for Homes, 2005).

1.2 The Performance of Insulation

As explained by Marsh (1979), all materials have the ability to transmit heat. A body will give up heat to a cooler surrounding by various methods until thermal equilibrium is reached. If the body is surrounded by a solid then heat will be transferred by ***conduction*** a process whereby neighbouring molecules of the material pass on temperature variations to one and other by atomic motion. Where a body is surrounded by a gas or a liquid this initial transfer by conductance will give rise to ***convection***, occurring where the area of surrounding free moving substance that is now "heated", will rise. This movement will produce ***convection currents*** where the movement of the rising free moving medium will cause "unheated" medium to be moved into position adjacent to the hot body where it in turn will be "heated". Where a body is in a vacuum the only method of heat loss is that of ***radiation.*** Thermal radiation is a direct result of the movements of atoms and molecules in a material. Since these atoms and molecules are composed of charged particles (protons and electrons), their movements result in the emission of electromagnetic radiation (photons), which carries energy away from the surface.

The rate at which an insulation material will ***conduct*** heat depends on its ***conductivity*** (k). This is a property of the material and its thickness. Some materials have a greater ability to conduct heat than others, an ability usually dictated by the structure of the material. The more dense and compact the structure the quicker the heat will be conducted. Those materials of a more "open" structure have a greater resistance to the passage of heat. Hence the best insulating materials are lightweight, usually of a cellular or fibrous nature. It is worth noting however that this generalisation does not apply to materials that insulate by reflecting radiant heat such as aluminium foil-faced building paper. However, These metallic or metallized reflective membranes must face an air-filled, gas-filled, or evacuated space to be effective (Marsh, 1979).

1.3 Types of material available

There are many types of insulation but all have the same basic property of reducing unwanted heat transfer. As categorised by Al-Homond (2005) the materials used to produce thermal insulation are either:

Inorganic Materials

- *Fibrous materials* such as glass, rock, and slag wool.
- *Cellular materials* such as calcium silicate, bonded perlite, vermiculite, and ceramic products.
- *Metallic or metallized reflective membranes.*

or Organic Materials

- *Fibrous materials* such as cellulose, cotton, wood, pulp, cane, or synthetic fibres.
- *Cellular materials* such as cork, foamed rubber, polystyrene, polyethylene, polyurethane, polyisocyanurate and other polymers.

Accordingly, insulating materials are produced in different forms as follows:

- Mineral fibre blankets: batts and rolls (fibreglass and Rock wool).
- Loose fill that can be blown-in (fibreglass, rock wool), poured-in, or mixed with concrete (cellulose, perlite, vermiculite).
- Rigid boards (polystyrene, polyurethane, polyisocyanurate, and fibreglass).
- Foamed or sprayed in-place (polyurethane and polyisocyanurate).
- Boards or blocks (perlite and vermiculite).
- Insulated concrete blocks.
- Insulated concrete form.
- Reflective materials (aluminum foil, ceramic coatings).

1.4 Current Market

The UK thermal insulation market in 2006 was estimated to have reached £1075 million at contractors' prices. Growth of the market accelerated since 2002, due to changes in the building regulations and government initiatives that have boosted the building thermal insulation market, this has led to a peak increase of 11% in 2003. As such, growth has been a feature of the market in the period between 2002 and 2005, culminating in an increase of 29% in nominal terms. Continued strong growth is expected to be generated in the building thermal insulation sector, reflecting anticipated growth in the construction sector, the further tightening of thermal insulation standards in the building regulations and the extension of the government's EEC programme. Demand for thermal insulation is thus anticipated to grow over the next five years with the value of the market being forecast to increase by a further 23% by 2011 (Market and Business Development, 2007).

1.5 Energy balance

Thermal insulation is used as a passive measure in the reduction of heat energy loss, thus it requires no further energy inputs to perform its task once installed. The amount of energy saved by using insulation materials as opposed to not insulating a building, should in general far outweigh the amount of energy used in the materials production. For example, mineral wool is produced by melting a mixture of sedimentary stones at very high temperatures (over 1000°C) in a furnace, then spinning the molten material into an open wool like structure (described in more detail later in 2.6.4.1). Over 50 years of use a very efficiently produced mineral wool product (in this example Rockwool Loft Roll) is able to save over 100 times more primary energy than was used for its production, transport and disposal (Rockwool, 2006b). For this reason, thermal insulation has been identified as playing a vital role in the reduction of energy usage in the construction sector (DTI, 2003).

1.6 Purpose of study

Non-food crops are renewable industrial feedstocks and in many cases their production can require lower levels of energy inputs, consumption of fossil and other resources and generate fewer overall environmental impacts that alternative materials. However, natural fibre insulation materials cannot simply be presumed to have 'superior' environmental credentials, these aspects need to be examined objectively and on a case-by-case basis.

Life Cycle Assessments (LCAs) have been conducted on insulation materials and positive results have been used in product promotion by manufacturers. In some cases, LCA results have also been used to discredit other manufactures or materials. One such example of this is an LCA commissioned by Rockwool to compare Rockwool stone wool insulation material with flax and paper fibre alternatives. The report concluded that the example of flax-based insulation material in the study had a poor environmental rating. This finding was used subsequently in a lawsuit by the insulation industry association of Germany against the EU Commission for endorsing the German government's decision to subsidise flax based insulation (Rockwool, 2004). It is clear from this example that LCA data and its interpretation can have an important role to play in evaluating the environmental 'pros and cons' of insulation products.

The National Non-Food Crop Centre (NNFCC) believes that appropriate use of non-food crops can provide a route to delivering environmental and sustainability benefits and support for the UK Government's objectives for sustainable development. However, there is currently a lack of reliable data regarding the environmental impacts of natural fibre based insulation materials relevant to the UK. This study was produced in conjunction with a report commissioned by the NNFCC, with the aim of supplying just such data. The NNFCC study was funded by DEFRA.

1.7 The study

The overall purpose of this study was to develop a scientific and transparent evidence base through the use of Life Cycle Assessments, to ascertain the environmental impact of non-food crop insulation materials, in comparison to conventional ***market leading*** materials that have been promoted as having a low environmental impact. Due to the large current differential in production scale between the Natural fibre and conventional materials, a further study regarding potential near future scale up was also conducted.

Though this study was considered to be robust and transparent, the assumption that the natural fibre and conventional materials would perform identically over a 60 year period was questioned when considering the water sorption characteristics of the fibres in question. Heat released due to moisture adsorption and heat absorbed during moisture desorption for example, could have a significant impact over the lifetime of an insulation product, but this has not been considered before. As such, an in depth study into the effect of certain water sorption characteristics was performed including a study of the "heat of wetting" and its potential effect on the initial LCA. As this particular study and its relevant literature review is very different to the initial LCA work it is presented in a separate section (part 2). An outline of the study is presented below:

Part 1

Chapter 2 is a literature review covering the history and current "state of the art" concerning modern LCA practise. This section also introduces the studied materials.

Chapter 3 outlines the goal and scope of the study, describes the comparative functional unit to be studied. The data collection process and inventory for the studied products is also presented prior to the initial study results.

Chapter 4 includes a sensitivity analysis of the data supplied by the conventional material manufacturers, a marginal analysis of the natural fibre materials in order to ascertain areas of excessive environmental impact. Stemming from this, a study of potential near future optimisations is then presented.

Part 2

Chapter 5 is a literature review covering the moisture sorption and heat of wetting of natural fibres concentrating on plant fibres.

Chapter 6 introduces the use of a dynamic vapour sorption (DVS) analyser through experiments on sorption characteristic of 1) various plant fibres, and 2) the effect of delignification.

Chapter 7 presents a methodology of calculating the (integral) heat of wetting using the DVS analyser and a calculation of the possible effect of this phenomenon in a plant fibre insulation product.

Concluding Chapter

Chapter 8 draws together the conclusions and recommendations of the preceding chapters to present a concise summary of the study and issues raised by it.

Part 1

The Life Cycle Assessment of Natural fibre Insulation Materials

2 Literature review of Life Cycle Assessment

2.1.1 Introduction

Life Cycle Assessment (LCA) has been defined by the International Standards Organisation (ISO) as follows:

"LCA is a technique for assessing the environmental aspects and potential impacts associated with a product by compiling an inventory of relevant inputs and outputs of a system; evaluating the potential impacts associated with those inputs and outputs; interpreting the results of the inventory and impact phases in relation to the objectives of the study" (BSI, 1997)

In this definition the term product refers to both products and services and the term system refers to an industrial system *i.e.* raw material extraction, processing, manufacture, use and disposal. This ISO definition of LCA will be used in this report.

The technical framework for life cycle assessment consists of four components, each having a very important role in the assessment. They are interrelated throughout the entire assessment and in accordance to the current terminology of the ISO. The components are (1) goal and scope definition, (2) inventory analysis, (3) impact assessment and (4) interpretation.

In order to understand how these components evolved and how they interact a brief history of the modern LCA is presented below, followed by an abbreviated methodology for the production of an (ISO 14040 style) LCA. These have been presented here to aid understanding of the main LCA study that follows, especially with regard to the terms used and style of presentation.

2.1.2 History of LCA

Harold Smith presented what was possibly the first Life Cycle Assessment style publication at the World Energy Conference in 1963. In this he presented his "cumulative energy concept" as part of a study of energy requirements for the production of chemical intermediates and products. This concept of finding a way to cumulatively account for energy use (and thus predict future resource supplies) stemmed from the growing concerns over limited energy and raw material resources around this time (Curran, 2006).

Similarly, due to an increase in scientific knowledge regarding human impact on the natural environment, the 1960's also saw growing concern over the environmental impact of certain materials. In 1969 research was commissioned by the Coca-Cola Company (later published in 1974) which compared the release rate to the environment of varied beverage containers (Hunt *et al*, 1974). By sequentially studying which container had the lowest release rate and hence also the least requirement for the supply of natural resources, a methodology was developed which laid the foundation for the current methods of life cycle *inventory* analysis (Curran, 2006). Inventory in this case meaning a detailed list of the inputs and specific outputs involved with each material.

After this initial work the process of quantifying the resource use and environmental release of products became known as; Resource and Environmental Profile Analysis (REPA) in America. With the onset of oil shortages in America approximately 15 of these REPAs were performed between 1970 and 1975 giving rise to a standard inventory methodology. As environmental concerns shifted to hazardous waste issues so too did the focus of these studies, with around two studies being produced each year and the methodology continuing to adapt and become more robust towards the 1980s.

Though some REPAs were conducted in Europe (for example by Dr Ian Boustead in the UK), the establishment of an Environmental Directorate (DG X1) by the European Commission saw European LCA practitioners develop parallel systems to those being used in America. These methods where often referred to as an "Ecobalance" in Europe. When solid waste became an issue in 1988 these LCAs were again used to analyze the problems by producing relevant inventories.

A large step towards the modern LCA came in the early 1990s with a methodology developed by the Society of Environmental Toxicology and Chemistry (SETAC) which added an environmental impact assessment phase onto the relatively established inventory stage (Curran, 2006). Thus for the first time the reader of such reports was presented with a scale of magnitude regarding the environmental impact resulting from the listed outputs in the inventory type studies. In some cases this would include the grouping together of similar outputs from the inventory phase. For example carbon dioxide and methane emissions could be grouped together to be expressed as a single impact from a system *i.e.* Global Warming Potential (GWP) expressed as grams of carbon dioxide equivalent.

In 1991 however, the popularity of LCA style studies was tarnished when the use of LCA studies for the use in ***product promotion*** was denounced by eleven states in America after concerns over cases of inappropriate use. This denouncement was initiated in recognition that there was no consensus as to how this type of environmental comparison could be advertised "non-deceptively". This action, along with pressure from other environmental organisations to standardise the LCA methodology, led to the development of the International Standards Organisation (ISO) 14000 series during the period of 1997 to 2002 (Curran, 2006). This set of standards which include the recommendation of an unbiased peer reviewing process is widely accepted as the frame work for the modern LCA.

Also during this time the Society for the Promotion of LCA Development (SPOLD) was founded in 1992, to develop and promote a commonly acceptable LCA practise. This included a standard format of data that was compatible with varied LCA software and is still widely used today (SPOLD, 1993).

2.1.3 The Modern LCA

The life cycle assessment standards defined by ISO 14040-43 are at the following:

IS0 14040 General Principles and Framework

Provides the basic description and framework for LCA upon which the remaining LCA standards are based. This standard also defines the "comparative assertion" requirements, including critical review (BSI, 1997).

IS0 14041 Goal and scope definition and inventory analysis.

Establishes at the outset the goals, purpose, audience, scope, and stakeholders that will be impacted or influenced by the results. This information influences the actual conduct of the LCA study. The inventory analysis portion is where the resources and emissions related to the product system are quantified (BSI, 1998).

ISO 14042 Life cycle impact assessment.

The phase of life cycle assessment aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts of a product system (BSI, 2000a).

ISO 14043 Life cycle interpretation

The interpretation phase of an LCA is where the significance and relative contributions of the results are broken down and analyzed (BSI, 2000b).

The use of the ISO 14040 series by many LCA practitioners is largely responsible for the current acceptance of LCA which is now becoming recognised within the scientific community, governments and organisations as an established and useful environmental assessment tool (Harris, 2004).

2.2 LCA Methodology

An important concept regarding the ISO LCA methodology is that the production of an LCA should not be thought of as purely a sequential methodology, as all the phases are ***interactive*** (BSI, 1997). This can be seen in Figure 1 where the first three of the previously introduced phases, *i.e.* goal and scope, inventory, impact assessment are dependant on each other through the phase of interpretation. To achieve this, each phase of the methodological framework is required to interlink with the other phases during the study. By doing this the study can adapt in order to accommodate unexpected findings during the study that would have resulted in a less meaningful study.

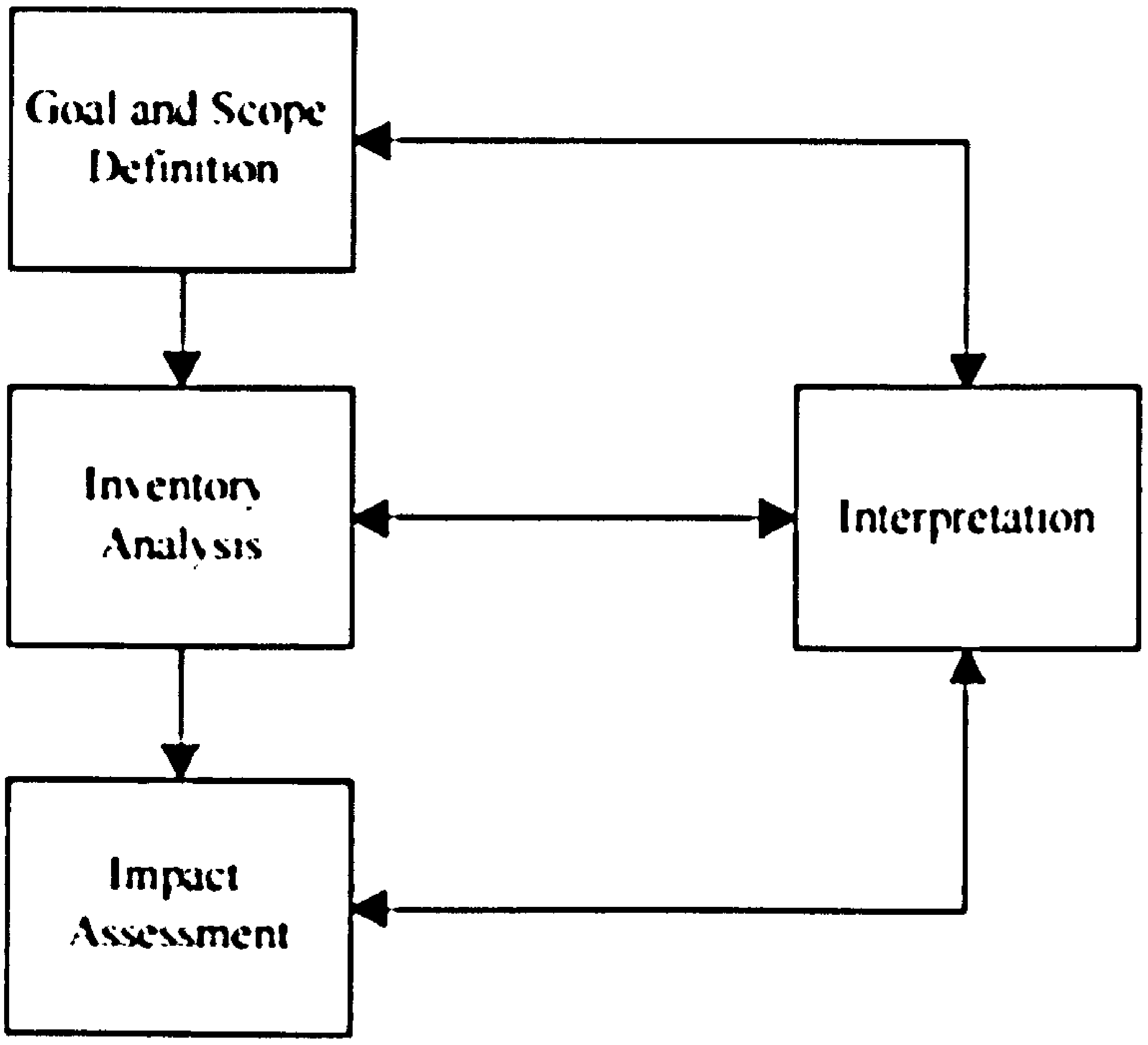

Figure 1 The Components of an LCA adapted from BSI (1997)

As a reference point for the reader, what now follows is a summary of the LCA methodology produced by the ISO LCA standard series 14040-14043.

2.2.1 Phase 1: Goal and Scope Definition

The Goal and Scope Definition of an LCA, sometimes referred to as the initiation phase, should specify the purpose of the study and then present a detailed plan of how the LCA study will be conducted (BSI, 1998).

Goal

The definition of the goal aims to clearly state the LCA study objective and the reasons behind this objective. The LCA initiator (commissioning body), the LCA practitioner and the intended audience are also described (BSI, 1998).

Scope

The purpose of the scope component is to produce a conceptual model of the inputs, processes, boundaries and outputs of the studied system. This model should display the simplifications and assumptions taken by the practitioner and disclose the structure of the subsequent LCA phases (BSI, 1998). As such the scope commonly contains four subcomponents; function, system boundaries, data quality requirements and critical review considerations:

- The ***function*** component requires the function of the system studied, the functional unit and a reference flow of the LCA to be defined. These definitions must relate to the objectives presented in the goal definition. The function is the role of the studied product system, for example *coppice wood fuel consumption*. The ***functional unit*** is a quantification of the function for the purpose of the LCA study *e.g. production of 20 MJ of* *energy*. The ***reference flow*** refers to a quantified amount of the product that is required to produce the functional unit. However, when making a comparative LCA study it is imperative that the function, functional unit and reference flow of each product or service system is equivalent to generate unbiased results. So our example reference flow could be the *production of 1 kg of chopped poplar wood* or *1.1 kg of chopped willow*, where the quantities required are slightly different due to willow having a slightly lower calorific value (Energy Research Centre of the Netherlands, 2007).

- The ***system boundaries*** define the "unit" processes to be included in the studied system. Ideally, the flow of each element would be modelled but this is rarely considered due to the complexity of most products studied. As such, decisions must be made regarding which of the unit processes shall be modelled and to what level of detail. This "cut off" should be performed at a point where further studies would not notably change the overall concussions of the study, *i.e.* where a further process or level of detail is deemed insignificant by the practitioner. As part of the system boundary exercise decisions are also made regarding which releases to the environment shall be evaluated and the level of detail in this evaluation, *e.g.* which environmental impact categories to use in the study. All decisions in this stage (*i.e.* to omit life cycle stages, processes or input/outputs) should be clearly stated and justified. It should also be considered in a comparative LCA that the system boundaries must be equivalent (BSI, 1998).

- The ***data quality*** section should provide information and assumptions about the data that is collected. Such data may be collected from the production sites associated with the unit processes (***primary data***) or may be obtained or calculated from published sources (***secondary data***). In practice all data categories may include a mixture of measured, calculated or estimated data (BSI, 1998).

- A ***critical review*** is often required to increase transparency and credibility before a study can be made public, but is an optional component of the study. If an LCA study is critically reviewed, there must be a statement about the type of critical review *e.g.* external or internal, the expertise of the reviewers, reasons for the review *etc.* (BSI, 1997).

2.2.2 Phase 2 – Inventory Analysis

This second phase of the LCA is concerned with the data collection and calculation procedures. After completing phase 1 of the LCA (the goal and scoping section) an initial plan for conducting the LCA study will be formulated and it is from this the initial plan that the life cycle inventory analysis (LCI) can be formed. The inventory stage comprises of three stages, data collection procedure definition, data collection, and inventory results calculation (BSI, 1998).

2.2.2.1 Data Collection Preparation

In order to collect consistent and meaningful data the collection process should be thoroughly planned, especially as the data collection may often span several reporting locations and published references. As such, the first step is to identify the ***system processes*** for which input and output data must be collected, this will generally include: extraction and processing of raw materials, manufacture of product, transportation of materials and products to markets, use by consumers, product disposal.

In order to identify these processes the production of a flow diagram representing each system process and sub-process (within the pre-defined system boundaries) is advised. From this process description the correct data enquiries can be planned, for example in the production of a questionnaire or a spreadsheet outline. During consideration of how these "blanks" can be filled, the most appropriate method for data collection can be decided. Though the collection of primary data (*e.g.* by physical measurement of site specific energy and material flows) should be a priority over the use of existing datasets (*e.g.* industrial averages), these secondary data should also be considered but only if they are directly relevant to the study.

2.2.2.2 Data Collection

The procedures for data collection can vary with each unit process in the different systems modelled by an LCA study. As such the data collection stage relies on a through knowledge about each unit process (as provided by the preparation stage). The descriptions produced are especially important to avoid double counting or gaps in the data. It is also important that each mass, energy or monetary flow is recorded in (or in a format where it can be converted to) comparable units.

Where the unit process has multiple inputs and outputs (*e.g.* the use or production of by-products) data relevant for later ***allocation procedures*** is required, such as the weight or monetary value depending on whether a ***mass*** or ***economic allocation*** is to be used. This may include data from outside the initial study boundaries. It is recommended that both are collected because the feed back process may later show one method to be un-suitable, for example following the sensitivity analysis conducted later in the study (where different scenarios are used to test how robust the final model is).

2.2.2.3 Inventory Results Calculation

Several steps are generally included in the data calculation stage, these include: the validation of data, relating data to the unit process and functional unit, data aggregation and also the refining of system boundaries if necessary.

- Data should be validated by ensuring flows into the system equal the flows out of the system (*e.g.* the mass of the product equals the sum of the components less any waste or by-products) and also by comparing the data used with similar data from other sources. This iterative data validation provides the LCA practitioner with the opportunity to improve or substitute poor quality data.
- The calculation stage should result in all system input and output data being referenced to the functional unit and can be accomplished by

normalizing the flows of all unit processes in the system to the functional unit. Using the previous example of *20 MJ of energy from coppice wood fuel consumption* would require all data to be relevant to *the production of 1 kg of chopped poplar wood.*

- During data calculation the system boundaries can be adjusted to include processes that have been found to have a significant impact on the LCA results or exclude insignificant processes. This interactive process is important to ensure the LCA is comprehensive without unnecessary data handling (BSI, 1998).

A large amount of data is normally collected and ***data aggregation*** prevents it from being unmanageable. The majority of modern LCA practitioners use LCA software packages to aggregate sub processes in to manageable figures and also to make inventory calculations for large datasets.

2.2.3 Phase 3 – Life Cycle Impact Assessment (LCIA)

The purpose of the LCIA phase is to examine the product system from an environmental perspective and provide information for further interpretation. This is achieved by sorting the calculated data into impact categories and category indicators connected with the previous LCI results. In terms of the ISO 14040 standard method there are both mandatory and optional elements (BSI, 2000a) as shown in Figure 2 below. These ***mandatory elements*** are required to make the study a life cycle assessment rather than a presentation of LCI results, they include: impact category definition, classification and characterisation.

Figure 2 Elements of the LCIA phase from BSI, 2000a

2.2.3.1 Impact Category Definition

Though there are no compulsory impact categories within ISO 14042, LCA practitioners have formulated baseline categories, which are used in the majority of reputable LCA studies. These baseline impact categories include: abiotic resource depletion, biotic resource depletion, global warming potential (GWP), stratospheric ozone layer depletion, acidification, human toxicity, ecotoxicity, photochemical ozone creation, eutrophication and solid waste generation (CML, 2001). LCA studies may need to include other categories that are specific to the study objective and the selection of utilised impact categories needs to be justified.

2.2.3.2 Assignment of LCI results (Classification)

The aim of the classification element is to assign the calculated LCI results to impact categories in order to highlight the environmental issues associated with the results. The relationship between the inventory result and its assigned impact category is described by a ***category indicator***, for example: methane is linked to global warming by infrared radiative forcing (BSI, 2000a). It is also possible that inventory results can be assigned to more than one category *e.g.* SO_2 is allocated in both acidification and human health.

2.2.3.3 Characterisation

The characterisation component involves the quantification of impact categories. Inventory results assigned to particular categories are aggregated to produce a single value for each category. This value is known as the ***indicator result***. The characterisation element is required to take account of the relative importance of each inventory result for a specific impact category. To do this the inventory result needs to be converted by ***characterisation factor***. The selection of the characterisation factor must be specified within the LCA study.

The calculations for the example of methane in terms of global warming potential are complicated by its effective lifetime in the atmosphere of 12 years. Thus, the global warming potential the 1 kg of methane has a potential of 72 kg CO_2 equivalent over 20 years and but 25 kg CO_2 equivalent over 100 years (IPPC Working Group 1, 2007). As such the correct characterisation factor must be used depending on the impact category.

In order to introduce some of the terms commonly used in the LCIA phase, below in Table 1 is a presentation of these terms (with corresponding examples regarding the impact category of climate change) for clarification. [a] = Intergovernmental Panel on Climate Change.

Table 1 Examples of terms in the LCIA phase from ISO 14042 (BSI, 2000a)

Term	Example
Impact category	Climate change
LCI results	Greenhouse gases
Characterization model	IPCC [a] model
Category indicator	Infrared radiative forcing (W/m^2)
Characterization factor	Global warming potential for each greenhouse gas (kg CO_2-equivalents/kg gas)
Indicator result	kg of CO_2-equivalents
Category endpoints	Coral reefs forest, crops
Environmental reference	Degree of linkage between category indicator and category endpoint

2.2.3.4 Optional LCIA Elements

The optional elements of the LCIA phase include normalisation, grouping, weighting and data quality assessments. They are generally used to convey relevant results in a way that can be understood by the intended audience. LCA practitioners have designed LCIA models to perform this, for example the Eco-Indicator 99 and CML baseline (essentially selected groups of impact categories with linked normalisation and weighting data) which used in conjunction with LCA software.

These optional techniques can increase the manageability, relevance and significance of the indicator results. However, they are all based upon value judgement rather than scientific knowledge and expertise, and thus introduce subjectivity to LCIA.

Normalisation calculates the magnitude of the indicator results relative to reference information. Reference information may include the total global population, specific emissions or resource usage over a specific period of time, also the amount *per capita* or even comparison with an alternative product system.

There are two types of LCIA ***grouping***. The first involves sorting impact categories with similar characteristics and grouping them together. For example, the Eco-Indicator 99 methodology uses damage factors to group impact categories into the three endpoints; human health, ecosystem quality and resources. The second type of grouping involves qualitatively ranking the impact categories to show their relative importance.

In the ***weighting*** process, indicator results are multiplied by numerical values, which have been subjectively chosen to depict their relative importance. When conducting a comparative LCA however, weighting should not be used since each impact will have a different relative importance for each different product system.

Data quality analysis can be used to provide a better understanding of the reliability of the data collected and also of the indicator results, for example to help distinguish any significant differences (BSI, 2000a).

2.2.4 Phase 4 – Interpretation

The aim of this final LCA phase is firstly to evaluate the completeness, accuracy and robustness of the results. This is conducted in reference to methodological choices and assumptions that where first made in the Goal Definition and Scope phase. Once this is completed the second aim is to identify the significant results generated in the preceding LCA phases and thus to present the final LCA study conclusions and recommendations (BSI, 2000b).

The evaluation of the LCA data and processes in this interpretation phase requires the following analyses:

- ***Completeness check*** – this is a qualitative procedure to ensure that all relevant information and data needed for the interpretation are available and complete.
- ***Sensitivity check*** – assesses the reliability of the final results and conclusions by determining whether they are affected by uncertainties in the data, calculations *etc*.
- ***Consistency check*** – determines whether assumptions, methodology and data are consistent with the original goal and scope

The completion of these checks may give rise to possible reworking of original data sets, calculations or presentations. This interactivity and final satisfaction of these checks will ultimately allow the final conclusions (and recommendations) to be drawn and presented to the intended audience (BSI, 2000b).

2.3 LCA software

Though it is possible to use commonly available spreadsheet programs such as Microsoft's Excel to handle the data required to produce an LCA, Various LCA specific software packages are available for purchase, such as those listed below:

- GaBi 4 (http://www.gabi-software.com/) produced by PE INTERNATIONAL and LBP-GaBi (University of Stuttgart)
- SimaPro 7 (http://www.pre.nl/simapro/) produced by PRé Consultants
- TEAM (http://www.ecobalance.com/uk_team.php) produced by Ecobilan
- GEMIS (http://www.oeko.de/service/gemis/en/index.htm) produced by Öko-Institut (Institute for applied ecology)

They are all similar in the respect that they are tools for handling large databases containing environmental data, such as emissions data for given products. With the more powerful and more expensive programs (such as GaBi and SimaPro) it is possible to present the calculated impacts of a number of different products in one graph or table with a given selection of impact categories. In general the programs are supplied with substantial databases of pre-analysed materials and processes that can be added together to model the product being studied. These databases are generally made up of publicly available or purchased data that has been produced by other LCA practitioners and as such data on specialist materials that are not on these databases are generally sold on separately in a format that can be read by most LCA software, such as the Boustead Model (Boustead, 2007).

2.4 Non-ISO standard LCAs

Besides the ISO 14040 standard there are many other types of "LCA" available to the construction sector, from guidelines regarding a simple calculation of the embodied energy or "carbon footprint", for example to satisfy the Carbon Trust funding application criteria (Carbon Trust, 2006) to the calculation of a specific range of environmental impacts such as the general The Institute of Environmental Sciences of Leiden University (CML) baseline (CML, 2001), the Council for European Producers of Materials for Construction (CEPMC) used by Schmit *et al.* (2003). Other LCA systems may include different weightings to the impact categories in order to present a comparable single score, such as the Building Research Establishment and their Environmental Assessment Method, BREEAM (BRE, 2007).

The BREEAM method is based on a full LCA of a given product producing an environmental profile in the form of selected environmental impacts. These impacts are then combined using an agreed weighting process that is reviewed by members of a governing committee, to provide a single score that is used to compare the product to those in the same category. A list of all scores is then used to distribute the products "green rating" based on a certain percentage of all products tested being given a particular rating (Tune, personal communication).

2.5 LCAs of construction materials

Asif et al. (2007) considers the LCA of a 3 bedroom house in Scotland, concentrating on the distribution of embodied energy and GWP by material used. They report that in the home studied 61% of the buildings' total embodied energy comes from concrete alone this is followed by ceramic tiles (15%) and timber (14%). This is broken down to a kg to kg basis and the embodied energy and environmental impacts of varied materials are reported in Table 2. It is worthy of note that a similar but more extensive table of materials and their effects on resources is presented in Berge (2000) that concentrates on material and energy resources.

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It is unfortunate that they do not discuss the impact of insulation in this report. But the figures stated do give a good idea as to the varied impacts from general construction materials and puts into context the results of other findings. It is not known whether the CO_2 sequestered by the timber is included in the environmental impacts presented in Table 2.

Peuportier (2001) compares the LCA of three single family houses in the French context. Though the report only displays the results from the modelled life cycle of the houses as a whole and not a break down of the contributions by material it is concluded that the house with the greatest quantity of insulation (of varied materials) has the lowest general impact in most impact categories, such as energy, toxicity and GWP100 (the global warming potential after a 100 year period). As part of a sensitivity analysis they modelled a variation in the conductivity of the wall insulation used in one of the houses, and found that a 25% variation of the conductivity, *i.e.* from 0.04 to 0.05 W/(m K), led to a 2.4% increase of the heating load and a 2.3% increase of the overall CO_2 emissions over the 80 year period considered.

2.6 The product systems studied

An introduction and description of the natural fibre and benchmark products studied are provided below along with indicative product system diagrams.

2.6.1 Isonat

The Isonat insulation material is originally a French product based on non-woven textile technology which was produced using waste cotton from the nearby apparel industry for Saint Goban. A very similar product was then sold directly from the manufacturer, Buitex (in Cours le Ville, near Lyon) to the French construction market. The product studied in this project is a variation of this but is still produced by Buitex. It incorporates UK grown and processed hemp fibre in an even blend alongside the French recycled cotton fibre. The use of the cotton fibre in this case was to keep the final cost down rather than any technical benefit. The final blend of materials is 35% hemp fibre, 35% recycled cotton fibre 15% bi-component polyester fibre and 15% fire retardant (by weight).

The materials' importation into the UK is managed by Gary Newman of Plant Fibre Technologies and is sold by select building outlets such as NBT (Natural Building Technologies) and EnergyWays. The current annual sales value of Isonat is around £500k (Newman, personal communication).

2.6.1.1 Hemp Farming

Hemp is a highly productive industrial crop and yields of up to 12 tonne/ha have been reported in the UK though in reality 6 tonne/ha appears to be a reliable average (Duckett, personal communication). Hemp is fairly tolerant to pests and diseases and is self-weeding so requires relatively low agricultural inputs compared to other fibre crops. Dual variety crops of hemp can produce seeds for oils and food as well as fibre and shive. However these varieties are not generally used where fibre production is important due to the low yield and reduced quality of the fibre. As hemp grows, as with all plants it absorbs CO_2 from the atmosphere. This carbon remains locked in the fibres throughout their use and so like many renewable materials it can display a negative CO_2 balance.

The hemp for the product is grown in the south east of England for primary processing at Hemcore, Near Bishop's Stortford, Hertfordshire. Most of the crops are currently grown within 100km of the factory, generally in East Anglia. Though the specifics of cultivation can vary from farm to farm due to the different soil requirements and machinery available, the basic processes remain the same:

Land, de-cultivated of the previous crop, is first sprayed with herbicide. The crop is then sown and the required fertilizer applied. After the crop has grown it is then cut and spread out in order to allow the crop to ret. The crop is then raked in and baled and stored on farm until it is required for delivery to the processing plant (Duckett, personal communication). A flow chart to represent this farming stage is shown in Figure 3.

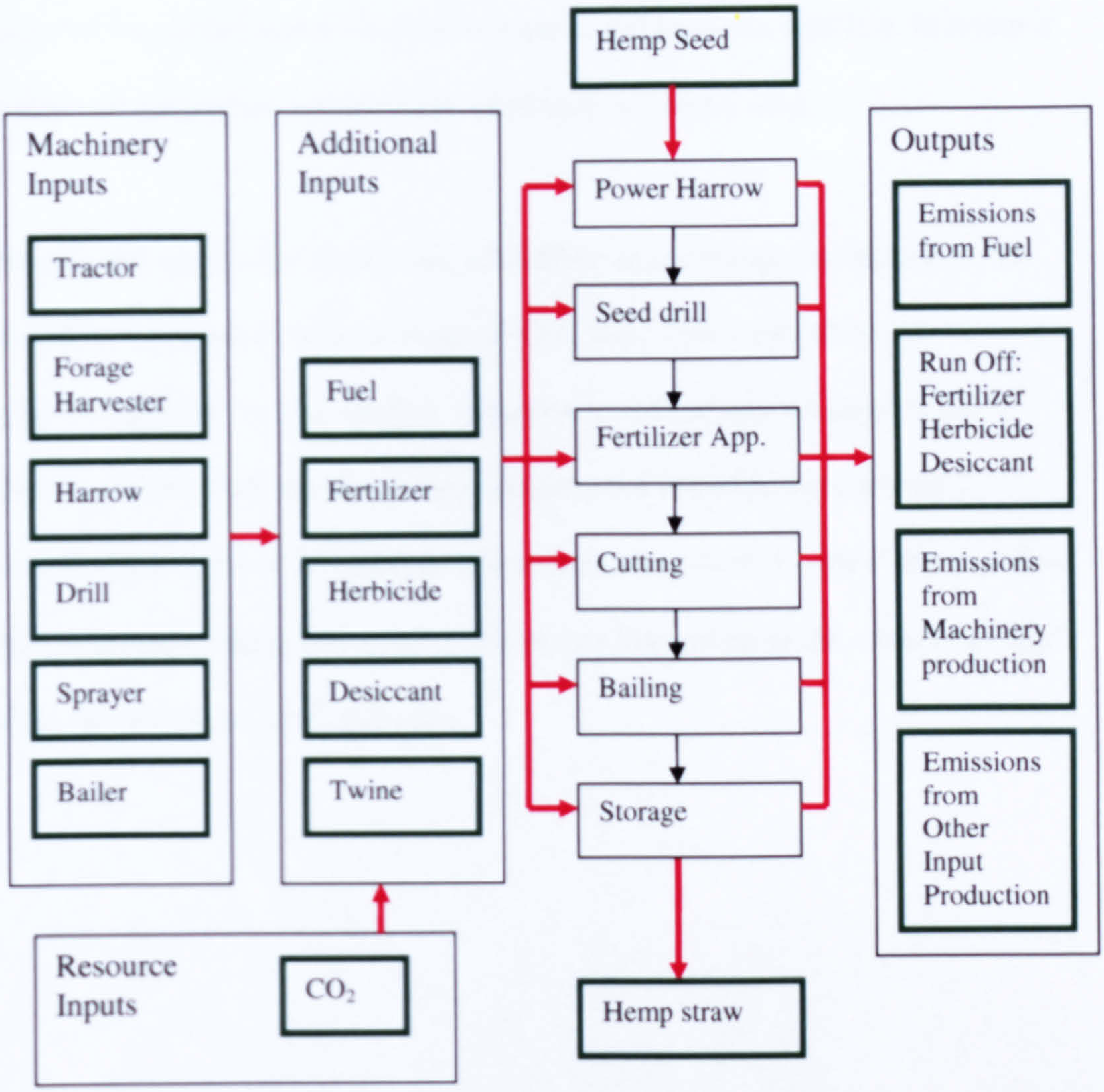


Figure 3 Flow Chart of Hemp Farming for Isonat product

2.6.1.2 Primary Processing

The primary processing carried out by Hemcore removes the shive (spongy core of the plant stem), dust and any other major impurities from the harvested hemp straw and produces a baled fibre for transportation to France. The main unit of the processing plant is a scutcher, which loosens the fibre from the shive working on the principle that the shive will break and fall away from the fibre as it is worked between reciprocating plates that "crimp" the stem. The Shive fraction is sold once bagged and palleted. The dust produced from the process is currently taken away for free and mixed with chicken manure and used as a fertilizer. In future it is likely be compacted into briquettes and sold as a fuel source.

The total energy used in the factory is 810kWh at an average throughput of 1.5 tonne/h of hemp straw, at an average of 16% m.c.. This varies from 0.4 – 2 tonne/h dependent on crop quality. A more streamlined unit is currently being planned which would require twice the energy but would process around 7 tonne/h of hemp straw (Duckett, personal communication). Figure 4 shows a flow chart to represent the primary hemp processing that produces the hemp fibre used in the Isonat insulation manufacture.

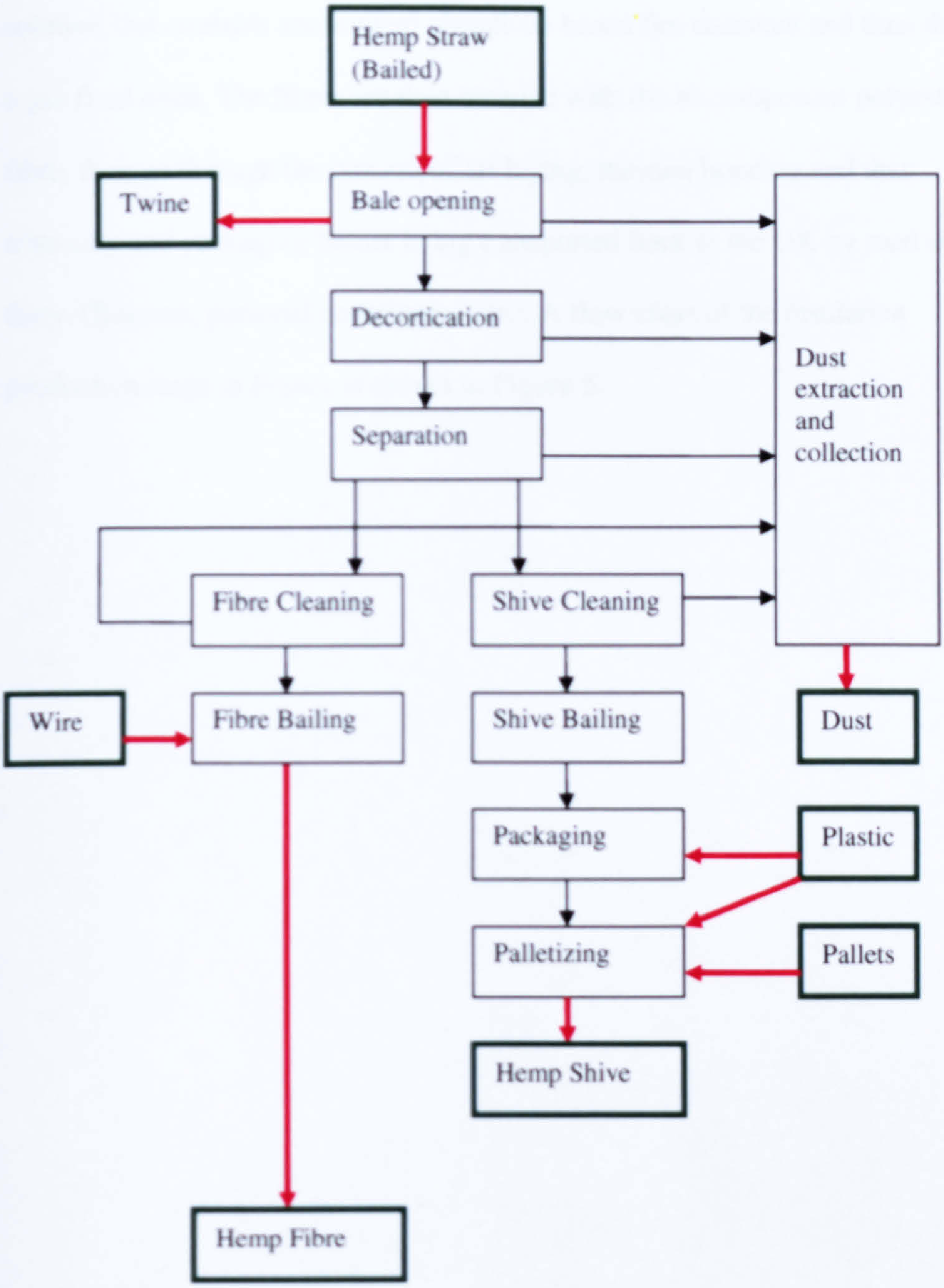


Figure 4 Flow Chart of Hemp Primary Processing at Hemcore for the Isonat product

2.6.1.3 Insulation Manufacture

At Buitex in France the fibre is blended with the recycled cotton fibre, a bi-component polyester fibre and a fire retardant then air laid and bonded to produce the Isonat Product. The hemp and the recycled cotton fibre is initially dipped in a solution that contains ammonium phosphate based fire retardant and then dried in a gas fired oven. The fibres are then blended with the bi-component polyester fibre, then go through the process of air laying, thermal bonding and then trimming and packaging before being transported back to the UK by road and ferry. (Buisson, personal communication). A flow chart of the insulation production stage in France is shown in Figure 5.

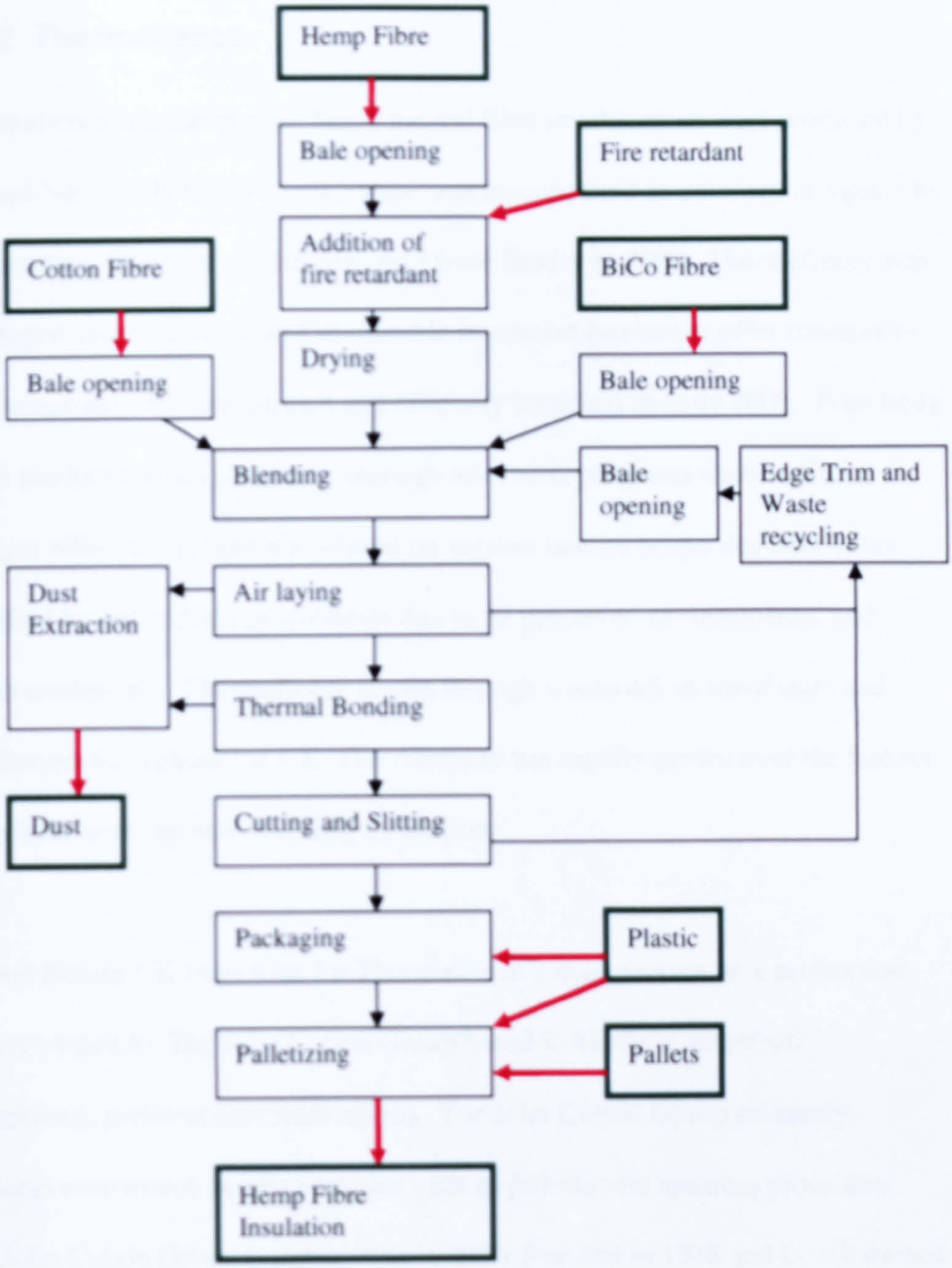


Figure 5 Flow Chart of Isonat Insulation Production at Buitex, France.

2.6.2 Thermafleece

Thermafleece is a sheep wool based natural fibre insulation product produced by Second Nature UK Ltd. Second Nature was incorporated as a limited company by its Directors, Christine Armstrong and David Baldry in 2000. Thermafleece was developed as a renewable and sustainable insulation product to offer consumers an alternative to the mainstream and officially launched in early 2001. Popularity in the product has also increased through television programs such as Grand Designs where it has been showcased on various feature properties after being specified by individuals or architects due to its perceived environmental and health credentials. Thermafleece is sold through a network of merchants and distributors throughout the UK. The company has rapidly grown over the last six years with turnover now reaching £1 million.

Second Nature UK buys time for Thermafleece's manufacture on a production facility owned by The John Cotton Group based in Mirfield, Bradford (Armstrong, personal communication). The John Cotton Group primarily produces non-woven bedding textiles such as pillows and mattress protectors. The John Cotton Group company was initially founded in 1918 and is still owned by the Cotton family with a turnover of circa £80 million. Since 1980 its home textiles sales have grown from £1m to circa £45m today.

2.6.2.1 Farming

Upland sheep are in general grown for their meat rather than for their wool. As part of good animal husbandry however, upland sheep are sheared to maintain the health of the animal. As soon as wool is sheared on-farm, it is insured by the BWMB (The British Wool Marketing Board) against any damage or loss. Having been transported to one of the 17 wool depots across the UK, in this case Bradford, the wool passes through a series of steps before entering the manufacturing process. Wool is packed into standard sized bales. It then later packed into bales suitable for local and international transportation. The bales weigh in the region of 340 kg, and are made up into sale lots of approx 8 tonnes (24 bales) of raw or "greasy" wool, as it is known. The wool used in the production of is classed as a "waste" product of sheep rearing and husbandry and its production is not included within the system boundary of the study. The reasoning for this is explained further in the data collection section of the study (Paragraph 3.3.3.1).

2.6.2.2 Scouring and rinsing

The fleece is sent to one of two scouring plants in bales from collection depots after auction in Bradford. The fleece is ether sent to Haworth Scouring Plant in Bradford (Figure 6) or Thomas Chadwick and Sons in Dewsbury. It is often contaminated with natural substances that must be removed before further processing can be carried out.

Figure 6 Picture of Haworth Scouring Plant in Bradford

Wool scouring involves blending the wool, de-dusting then washing in a series of 4 hot detergent bowls which is followed by a series of 4 rinsing tanks to remove lanolin, dirt and sweat from the greasy wool. The "greasy wool" contains 70% of wool worth and about 1% of lanolin with the remainder being of no economic interest (Whitaker, personal communication). The values of these products are not disclosed here out of respect to supplier confidentiality. As part of the scouring process the fleeces are dipped in a solution containing disodium octaborate tetrahydrate borax to protect the wool from fire and insects (Armstrong, personal communication). It is then dried to about 20% moisture content.

The wastewater from the scouring and rinsing process passes to Yorkshire Water for effluent treatment (Sagar, personal communication). The cleaned wool can be transferred pneumatically by overhead conveyors straight to the blending bins. Typically the bins holds 3-5 tonnes of scoured wool before packing commences, (Haworth Scouring Company, 1999). For packing, there are presses which are equipped with weight-box devices to give consistent bale weights to be sent to the insulation material manufacturer the John Cotton Group. Figure 7 shows a flow chart to represent the primary wool processing that produces the clean raw wool used in the insulation manufacture.

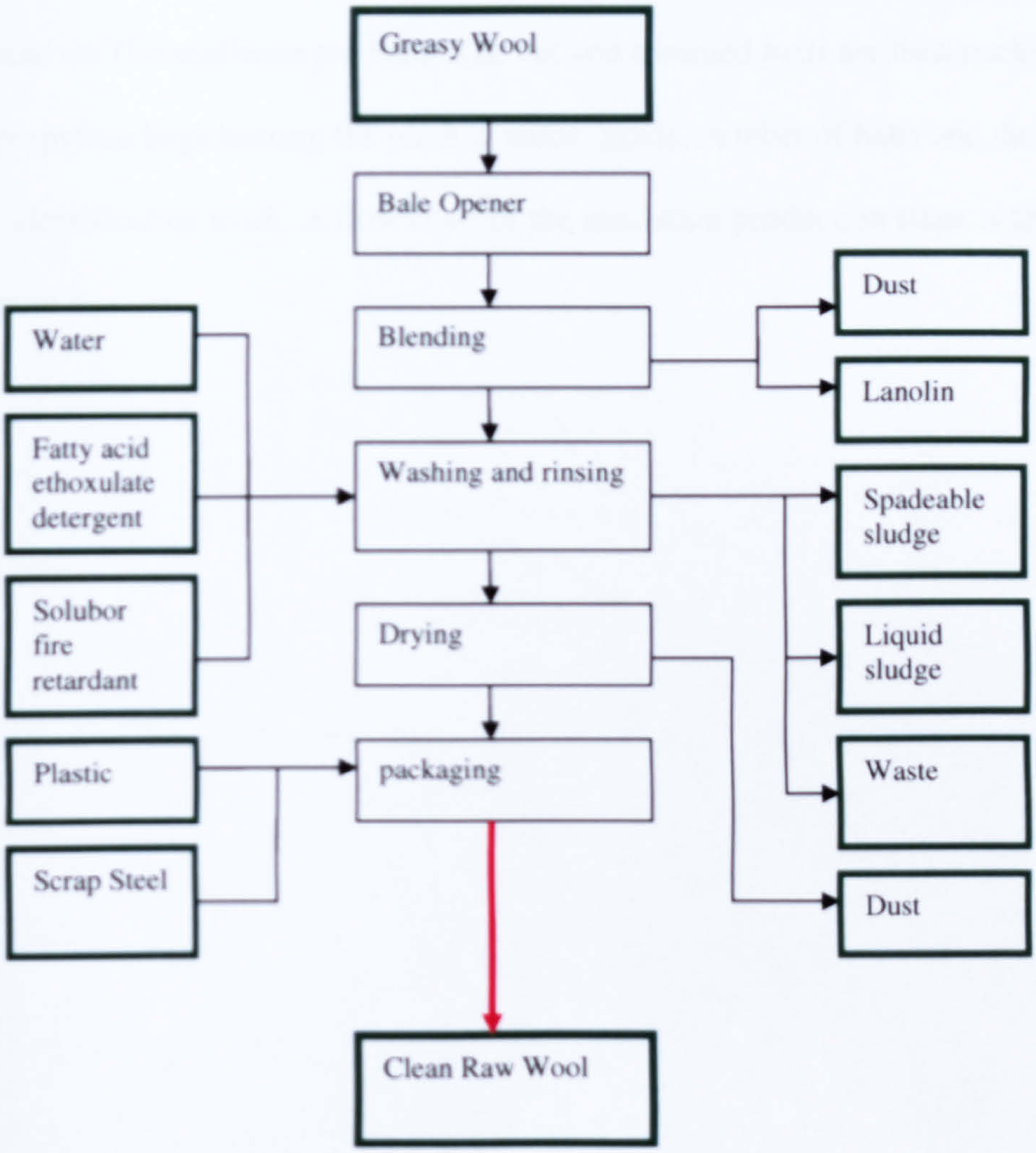


Figure 7 Flow Chart of Thermafleece Primary wool processing at Haworth Scouring

2.6.2.3 Manufacturing

The manufacture of Thermafleece involves a blending, air-laying and thermal bonding processing. Thermafleece is produced by metering a blend of wool and binding fibre (a bi-component polyester), which is then formed into a three dimensional web to a specific density as specified by Second Nature. This web is then held together through carding, and by use of "through air" bonding which forces the binder to cross link with the wool fibres. Any process or trimmed waste is reused on Thermafleece products. The cut and trimmed batts are then packed in polypropylene bags bearing the product name, grade, number of batts and the BBA identification mark. A flow chart of the insulation production stage is shown in Figure 8.

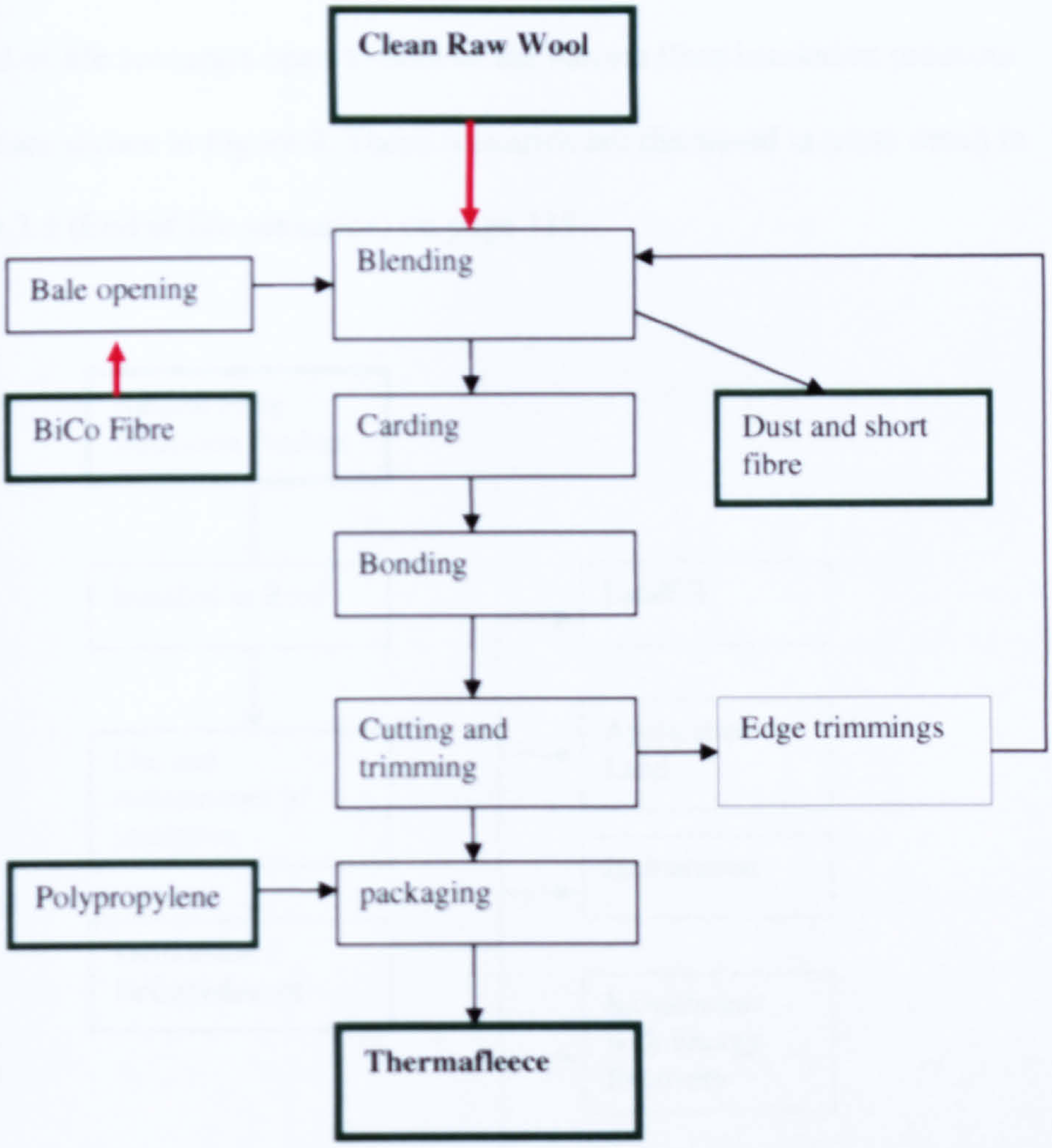


Figure 8 Flow Chart of Thermafleece Secondary Processing at John Cotton Manufacturing

2.6.3 End of life scenarios of natural fibre insulation products

The end of life scenarios open to both of the natural fibre insulation products studied are shown in Figure 9. These scenarios are discussed in more detail in Section 3.5 (End of life scenarios) on page 119.

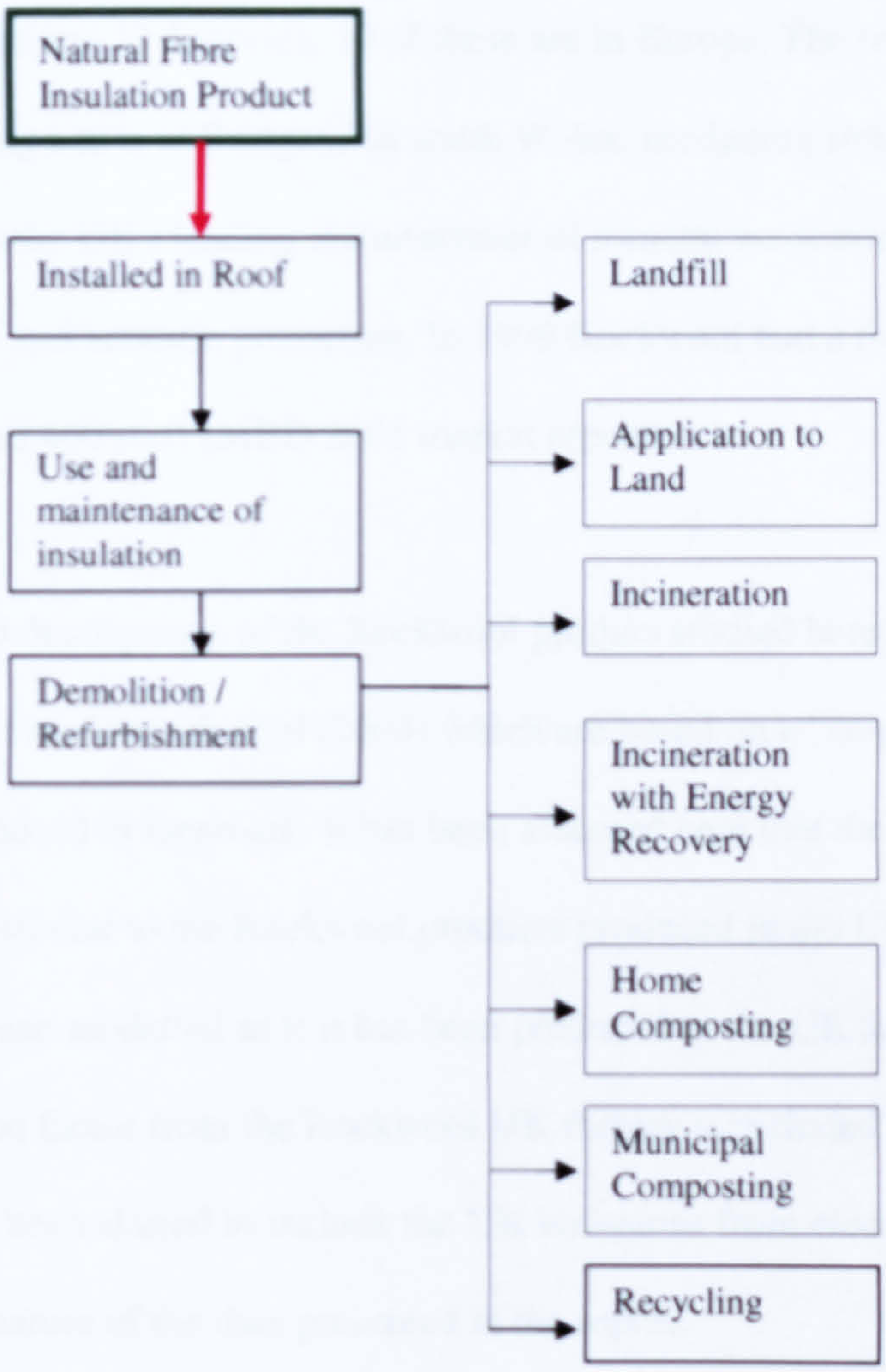


Figure 9 Flow Chart of In Use and End of Use Scenarios for the Natural Fibre Insulation Materials

2.6.4 Rockwool

Rockwool has been chosen as a benchmark product for the study as it is considered to be a market leading product in both popularity and low environmental impact.

Rockwool Ltd has 22 factories, 19 of these are in Europe. The one UK manufacturing site is at Bridgend in south Wales, producing stone wool. Rockwool is the UK's leading manufacturer of mineral wool insulation for thermal, fire and acoustic protection. In 1999 Rockwool had a turnover of £52M and employed 460 staff (MBD 2001 market report).

The data and descriptions of the Rockwool product studied here have been taken from a report by Schmidt *et al* (2003) which are based on a "stone wool HT" product produced in Denmark. It has been assumed here that the Danish product is the same or similar to the Rockwool products produced in the UK. This being the case it has been modelled as if it has been produced in the UK and thus only a transportation factor from the Rockwool UK factory is included in this study. The data has not been altered to include the UK emissions from electricity due to the aggregated nature of the data presented in the report.

The Rockwool batt is a medium density insulation product of 32 kg/m^3 and has a thermal conductivity of 0.037 W/mK. The Rockwool Product is 77% virgin raw material mainly in the form of diabase (igneous rock), Gotland stone (sandstone), limestone, cement and bauxite The remaining 23% are classed as waste materials. Rockwool also consists of a small amount of a synthetic thermosetting binder

(8%) to stabilise the fibres and make them water repellent. 0.3% of mineral oil is also added to seal the surface against dust production (Schmidt *et al*, 2003).

2.6.4.1 Production

The production process of mineral wool is very similar to that of glass fibre insulation, with only a difference in raw material and furnace type (cupola furnace as opposed to a melting furnace). Rockwool is made by melting the quarried diabase rock and recycled slag briquettes with the other raw materials in a coke heated cupola furnace at 1500 °C, then drawing out the minutely thin fibres by means of a spinning unit. The molten mineral matter cools rapidly as it is spun into the fibrous product. The binder and oil are added during this process and it is subsequently reheated to around 200 °C to cure the binder and stabilise the material before it is trimmed and cut to the required size ready to be packed as presented below in Figure 10.

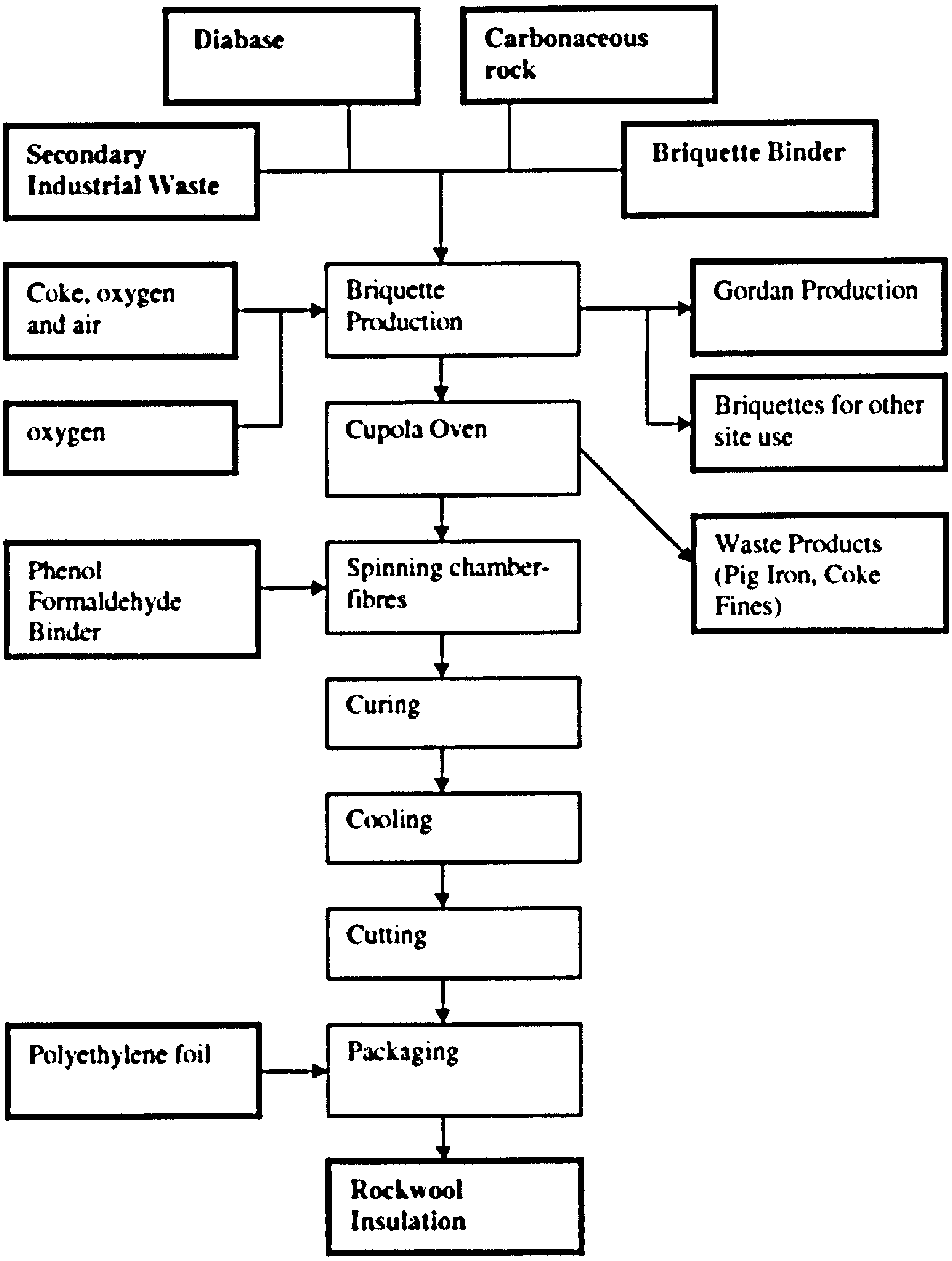


Figure 10 Flow Chart of Rockwool Processing adapted from Schmidt et al. (2003)

2.7 *Previous LCAs of related insulation materials*

2.7.1 Introduction

There is currently a limited amount of publicly available reports on the LCA of insulation materials. Most of those available are not presented in their entirety and are generally used to present the environmental credentials of a material in a favourable way for advertisement purposes. Many of these LCA reports have been compiled, generally by varied LCA consultants, in order to produce data for a "green rating" such as the Building Research Establishment Environmental Assessment Method (BREEAM) and their Green Guide to Specification (BRE, 2007).

2.7.2 Flax and hemp fibre based insulation materials

In a recent overview of flax and hemp as a raw material for thermal insulation by Kymalainen and Sjoberg (2007), which covers ninety nine references, only two of these were relevant to LCAs. The two mentioned are that of Behring and Murphy (1997) and Schmidt *et al.* (2004a). From extensive further searches no other references appear to be available in this area. What is reported by Kymalainen and Sjoberg (2007) are the basic conclusions from these two LCAs. The first by Behring and Murphy (1997) reports that there is a **lower** usage of energy and CO_2 emission for a flax based insulation product compared to a glass wool product. The second by Schmidt *et al.* (2004a) report a **larger** usage of energy and CO_2 emission for a flax based insulation product against a stone wool product –

produced by Rockwool. It is noted however that the Behring and Murphy (1997) figures are quoted are on a per m^3 basis whereas the Schmidt *et al.* (2004a) figures are reported in a per kg basis and thus not directly comparable against each other.

The references of Behring and Murphy (1997) and Schmidt *et al.* (2004a) are discussed separately in more detail below.

2.7.2.1 Behring and Murphy

Behring and Murphy (1997) set out to answer the question "Are flax based insulation products environmentally friendly?" and their general conclusion is that they are in comparison to a glass wool type insulation material. To do this they have followed the guidelines as presented by The Society for Environmental Toxicology and Chemistry (SETAC, 1992) "and related publications" in order to produce a comparative LCA. Their calculations for this were based on one hectare of land producing 1750 kg of "short" flax fibre along with 4480 kg of shive and 770 kg of seed. It was calculated that the fibre would produce 58.33 m^2 of insulation material using a "new short fibre technology". It is presumed that the insulation material is of 30 kg/m^2 density as it is difficult to ascertain whether any other binder or fire retardant was used in the product.

It was then calculated what emissions and energy would be saved by **not** using the same (58.33 m^2) quantity of a glass wool of an unspecified density or weight. The glass wool production data is referenced as originating from "Ceuterick (1993)" but unfortunately the reference is absent from the final reference list and it was not possible to track down either of the authors Behring H. or Murphy D.P.L. As such it was not possible to gain further data regarding its production, structure and performance.

The overall comparison includes the energy gain from the shive and seed fractions (16 and 25 MJ/kg respectively) and CO_2 abatement effect (74.4 g/MJ). However, from the results stated it is possible to calculate the energy consumption and emissions of the two insulation materials. This is shown in Table 3 below.

Table 3 The embodied energy and emissions of flax and glass wool insulation materials from Behring and Murphy (1997) showing two potential densities of the glass wool product.

Energy/Emission	Unit	Flax Per kg (assuming 30 kg/m^3)	Glass wool per kg (assuming 30 kg/m^3)	Glass wool per kg (assuming 20 kg/m^3)
primary energy	MJ	20.00	38.87	58.31
CO_2	g	1776.13	2515.54	3773.32
CH_4	g	2.18	4.80	7.21
N_2O	g	0.66	0.08	0.12
CO_2 Eq	g	2013.74	2659.17	3988.76
SO_2	g	1.39	1.83	2.75
NH_3	g	0.77	2.71	4.06
SO_2 Eq	g	5.60	8.27	12.40
Formaldehyde	g	0.04	0.30	0.45

The original data was displayed as the comparison between 58.33 m^3 of each insulation material. As the weight of flax fibre to provide this volume of insulation is given (1750 kg) and no other inputs such as binder materials are mentioned the approximate density of 30 kg/m^3 has been assumed in Table 3 above and later in the summary table, Table 4.

It is not possible to approximate the density of the glass wool product and therefore two potential densities of the glass wool material are presented in Table 3 in order to highlight the effect of comparing materials of different densities. Comparing the two assumed 30 kg/m^3 density figures of flax and glass shown in Table 3 will give proportionally the same results the same as presented in the original.

It is not clearly stated whether the carbon sequestered by the flax fibre (or its related portions) has been taken into account as part of the original abatement effect calculations, or if this abatement comes from a reduction in energy usage arising from the scenario stated of using the flax insulation instead of the glass material. It is possible to calculate that per MJ of embodied energy the presented materials differ in their CO_2 production. As the flax material is shown to produce a higher quantity of CO_2 per MJ than the glass material (89 and 65 g of CO_2/MJ respectively) it can be assumed that CO_2 sequestration has not been taken into account in this study.

Further information is unfortunately not available regarding the flax insulation and its composition and production as the references used are a personal communication with Vlaemynck C. and two German language references by "KTBL" (1996) and also Patyk and Reinhardt (1997).

2.7.2.2 Schmidt *et al.*

The other LCA report referred to in the flax and hemp literature review by Kymalainen and Sjoberg (2007) is that of Schmidt *et al.* (2004a), which is the first of a two part summary report (Schmidt *et al,* 2004b being the second part). The information in both of these summary reports is taken from a comprehensive previous report (Schmidt *et al* 2003) which was commissioned by Rockwool Ltd. In terms of satisfying the ISO 14040 standard the original report was peer reviewed and made publicly available in the journal LCA Documents.

Schmidt *et al.* (2003) presented a comparative Life Cycle Assessment of three insulation materials, Stone Wool (*i.e.* Rockwool HT stone wool), a flax based material and cellulosic paper wool. The flax based insulation product studied is that of Heraflax from Austria, produced from: 75% flax fibre 15% Polyester binder, and flame retardant materials: diammonium hydrogen phosphate (9%) and borax (1%). The data regarding the production of the product is referenced in the text as originating in "Krogh *et al.* (2000)" but a corresponding full reference is not given in the final reference list. The reference of "Krogh *et al.* (2001)" is presented elsewhere in the text suggesting a possible typing error, but it is not possible to tell if they are actually the same reference as the latter appears to be a non-English text. A general conclusion from Schmidt *et al* (2003) was that:

"With respect to potential environmental impacts, stone wool and paper wool are seen as the most preferable materials. Stone wool has the smallest consumption of primary energy seen over the whole life cycle, whereas paper wool performs best with respect to environmental impact categories like global warming, acidification, photochemical ozone creation and nutrient enrichment. Flax insulation has the largest impacts of the three materials in most of the impact categories examined in the study. This is to a large extent because of the binder used."

The analysis performed by Schmidt *et al.* (2003) appears to cover all major production aspects from farming to end product which would be expected for a natural fibre based insulation product. Where production data was not available for the report, reputable "stock" data appears to have been used. For example the energy consumption and related emissions of the farming practices were calculated from information reported by Weidema (1995).

As a conclusion the peer review, (conducted by Dennis Postlethwaite and presented in Schmidt *et al.*, 2003), reported that over all it was a well conducted LCA and complied with the ISO 14040 format. But did raise some issues, for example after noting that flax and paper wool products would be expected to have a similar profile due to both being derived from renewable agricultural sources he stated that:

> *"...it is perhaps curious why the total primary energy and electricity consumption for flax is considerably greater than that for stone wool, especially since production of the latter involves melting rock in a blast furnace prior to spinning the fibres"*

There are no notable agricultural or production practices included in the report that would appear to be excessive for the production of such a product. As such it would appear that ***this particular*** flax insulation product (Heraflax) does use more primary energy in production (including binder production) than the equivalent Rockwool product.

It was noted that some processes included in the study were however unlikely to occur in the production of ***other*** flax based materials as they where considered to be unnecessary. For example:

The processing stage of drying the flax straw by "tumble drying" was included at 1 kWh per litre of water evaporated taken from Energistyrelsen/F.R.I. (2000). It is possible to calculate that approximately 0.5 MJ was required per kg of finished product. This was considered to be a significant amount of energy to be included for an uncommon practice in flax processing (Newman, personal communication).

Schmidt et al (2003) also assumed that for every kilo of fibre produced for insulation materials, 0.956 kg of flax seeds and 3.08 kg of shives are produced as co-products and that these products would thus substitute other products on the market with the same function. For flax seeds, it was assumed that they would replace the same amount of linseeds. Shives were assumed to replace grass hay. It is however uncommon for a fibre crop to be left growing long enough to produce seeds as this results in very low quality fibre (Norton *et al.*, 2006)

Rather importantly with regard to CO_2 emission calculations, it is not mentioned whether the carbon sequestered by the plants' growth is taken into account in the final calculations.

The results of the Schmidt et al (2003) study are shown alongside those of Behring and Murphy (1997) and Ardente et al. (2007) in Table 4 which summarises their findings.

2.7.3 Kenaf fibre based insulation material

Ardente *et al.* (2007) produced a LCA of a **Kenaf-fibre insulation** board. The study also follows an ISO 14040 layout (BSI, 1997-2000b) and includes following the life cycle steps:

Land and crop cultivation, concentrating on the production of Kenaf (*Hibiscus cannabinus*) in Italy but also Morocco and other Mediterranean countries. Data regarding the consumptions of fertilisers and diesel was included but water consumption was not.

Transport along all stages. It was assumed that national transports occur by road lorry and cargo ships where employed for international transports from Mediterranean countries.

Cleaning, refining and insulation board manufacturing, A typical production cycle from an Italian factory was monitored.

Installation, maintenance and use, Concerning installation and maintenance, impacts where neglected. Regarding the use phase, the primary energy saving and the avoided CO_2 eq. emissions where estimated during the operation time.

End of life, Concerning to the disposal phase, the option of incineration is assumed. The CO_2 emissions from the combustion of the kenaf fibres have been not taken into account. In fact the combustion of biomass does not increase the greenhouse effect, since the amount of CO_2 emitted during the combustion is assumed to be equivalent to the amount of CO_2 which is captured during the growth. The electricity produced during incineration was not considered as a benefit in the environmental profile of the product.

The life-cycle impacts of the kenaf insulation material was compared with the performances of other products with a similar function, such as polyurethane, glass wool, flax rolls, stone wool, mineral wool and paper wool. Ardente *et al.* (2007) concluded that such a comparison shows that the highest impacts are related to synthetic materials, while the better performances are shown by mineral wools (this is presented in the summary Table 4 at the end of this section).

It was also noted that the overall ranking of the Kenaf insulation differed greatly if different end of life scenarios are adopted. In particular, the incineration with energy recovery and electricity production could decrease the global energy requirements of the Functional Unit (1.52kg) to 17 MJ from the original figure 59.4 MJ. A further reduction could also be obtained with the introduction of recycled materials into the manufacture process or with the local production of kenaf plants.

The external data for the comparisons is referred to as originating from The Boustead Model Version 4.4 (2001) and GEMIS Version 4.3 (no date), both of which are general LCA databases. In most cases it would appear the GEMIS database which can be accessed through its own LCA tool, refers to external data bases and in this case The Boustead Model was assumed. Though the stone wool, paper wool and flax data shares the same density and conductivity and identical emissions and energy consumption figures as those studied by Schmidt *et al.* (2003), the Boustead reference pre-dates this. Though the two references of Schmidt *et al.* 2004 a and b, are referred to this is only in the context of the environmental benefits of biomaterials in building products (they are referred to as Anders CS *et al.* (2004 1and 2) – Anders being the first name of Schmidt AC).

Having conversed with the producer of The Boustead Model Version 4.4, Dr Ian Boustead, (personal communication) it was apparent that the flax data in particular in the model originated from a "possibly German" manufacturer, but the details of which are not available as the database is 10 years old and considered obsolete and not presented in the current version of the model (version 5).

However, due to the ***identical*** data presented in Ardente *et al.* (2007) for the flax, paper wool and stone wool product data can been assumed to originate from Schmidt *et al.* (2004 a and b) or from ***exactly*** the same data from the manufacturers. It is however highly unlikely that an identical result would be obtained if a database had been constructed from original data due to the likely inclusion of different transport and end of life scenarios. As such it is most likely that the data originates directly from the Schmidt *et al.* (2004 a and b) references.

The relationships of these references are shown in Figure 1. The author for correspondence for the reference Ardente *et al.* (2007), has not replied to an enquiry regarding the origin of the data.

As a general conclusion Ardente *et al.* (2007) stated that the use of natural fibres involves a significant reduction of the environmental impacts derived from the employment of synthetic insulating materials, maintaining high "thermo-physic" and "noise-abatement" properties. They also noted that the energy saved during the service life of the insulation material outweighed the energy consumption related to the board manufacture.

2.7.4 Other insulation materials

Papadopoulos and Giama (2007) studied the Environmental performance of an unnamed stone wool product and an unnamed extruded polystyrene product. It is unclear where the original industrial data comes from for either material, as only data from the GEMIS software is stated. However, within the further reading section, reference is made to a "report on the research project" authored and entitled similarly to the aforementioned Schmidt *et al.* (2003) reference though no date is given (in this case however Klöpffer W and Hutzinger O are referenced as the primary authors and are noted as the editors of the Schmidt *et al.* (2003) report). Their results are displayed in Table 4 alongside other results. What is notable is the exceptionally low total energy consumption reported by Papadopoulos and Giama (2007) for both products when compared with the results of other insulation material LCAs. It is noted that the results reported by Papadopoulos and Giama (2007) are for a cradle to gate analysis (*i.e.* an accumulation of impacts from the production processes ***prior*** to leaving the factory gate) and does not include any impacts from installation or end of life scenarios. However these impacts are thought to have far less impact than the difference shown in Table 4 below.

2.7.5 Summary of literature results

Table 4 below is a summary of the reported environmental impacts of various insulation materials from the previously discussed references of : 1 Behring and Murphy (1997), 2 Schmidt et al. (2004b), 3 Ardente et al. (2007) and 4 Papadopoulos and Giama (2007)

The references used in Table 4 above are described here:

[1] Behring and Murphy (1997), ***cradle to grave results***, NB the density and conductivity of the Glass wool product are assumed to be the sam as the flax based product of the same author.

[2] Schmidt *et al.* (2004b) ***cradle to delivery results*** *i.e.* assuming 100% is recycled in road construction or similar low-grade recycling but also displayed identically in [3] Ardente *et al.* (2007)

[3] Ardente *et al.* (2007) ***cradle to grave results*** including: installation, maintenance, use and end of life *i.e.* Kenaf is incinerated but for Glass wool, Mineral wool and PUR the disposal is unknown.

[4] Papadopoulos and Giama (2007) ***Cradle to gate results***, *i.e.* not including delivery, installation or end of life scenarios.

3 Goal, Inventory Analysis and Impact Assessment

3.1 Introduction

This chapter covers the first three phases of an LCA study as outlined by ISO 14040. As such it covers the Goal and Scope Definition (phase 1), the Inventory Analysis (phase 2) and the Life Cycle Impact Assessment (phase 3). In this chapter the life cycle assessment of two natural fibre insulation materials: Thermafleece and Isonat, is presented and compared with a conventional insulation material made by Rockwool. An outline of the study is provided in the descriptions of the ***goal, scope*** and ***functions of the product system*** that follow.

3.1.1 Goal of the study

The goal of this study was to conduct a cradle to grave LCA of natural fibre insulation materials for construction use. In order to understand the significance of the environmental impacts of natural fibre insulation materials, the study included the assessment of a market leading insulation material for comparison. In order to avoid the production of what could be construed as a bias report, the market leading material was chosen for its' low environmental impact. *i.e.* it is assumed here that the benchmark product studied has already been awarded a BREEAM "A" rating which is the best rating currently possible *i.e.* of lowest environmental impact.

The Natural Fibre Insulation (NFI) products studied here are still in relatively early stages of product development. This being the case a major motivation for the study is not simply to compare how the NFI products compare against a low impacting market leader now, but to identify the main areas of improvements possible in the near and long term.

3.1.2 Scope of the study

The scope of this study was a cradle to grave assessment of different insulation materials following the principles of ISO 14040 series of international standards for LCA. The LCA included each stage of the raw material collection, processing, manufacturing, maintenance, demolition and final disposal of the insulation materials chosen for the study.

Studying what has been described as a low environmental impact conventional material alongside more novel materials gave perspective to their calculated impacts. Further analysis of predicted future developments and improvements to the products. For example through production scale up and the replacement of high impacting components, would give a wider picture of how these natural fibres could play a part in the insulation market. As such the study concentrated on two natural fibre insulation materials and one conventional material for the purpose of immediate comparison. These products are summarized below in Table 5:

Table 5 Summary table of products studied from information supplied from the manufacturers' data sheets.

	Non food crops Insulation Materials		**Benchmark Material**
Material	**Hemp and Cotton**	**Sheep's wool**	**Mineral wool**
Product name	**Isonat**	**Thermafleece**	**Rockwool batt**
Production Address	Cours la Ville, nr. Lyon, France	Mirfield, England	PenCoed, Bridgend, Wales
Length(mm)	1200	1200	1200
Width(mm)	400,600	400,600	400,600
Thickness(mm) available	50,75,100	50,75,100	100,150,170
Thermal Conductivity	0.039 W/mK	0.039 W/mK	0.037 W/mK
U value (W/m^{2}K)	0.16	0.16	0.16
Density (kg/m^3)	35	25	32
Thickness (mm) achieving U value 0.16W/m^{2}K for loft	225 (50+75+100)	225 (50+75+100)	200 (100+100)

Please note that the thicknesses specified in Table 5 have been rounded down to the nearest combination of thicknesses available. This is common practice in the construction industry as the contribution to the required U value from the plaster board and other loft materials are also taken into account.

Data collection was to be representative of relevant geographical locations for a UK usage with current technology. Data was acquired from site specific sources for natural fibres and their manufacture into construction insulation, from generic databases *e.g.* for transport, for energy consumption and from published/available information.

3.1.3 Functions of the product system

This study compared three different insulation materials in terms of their environmental impact, covering raw material acquisition, energy used, production, use and end disposal. Insulation materials all serve the same purpose - to improve the thermal and energy efficiency of domestic buildings.

This study focused on the loft part of the building. As a base-line, this project took a U-value (*i.e.* thermal conductance, or how easily heat is transferred across the insulation material) of 0.16 W/m²K, As this is the requirement stated by UK Building Regulations Document Part L as shown in Figure 12.

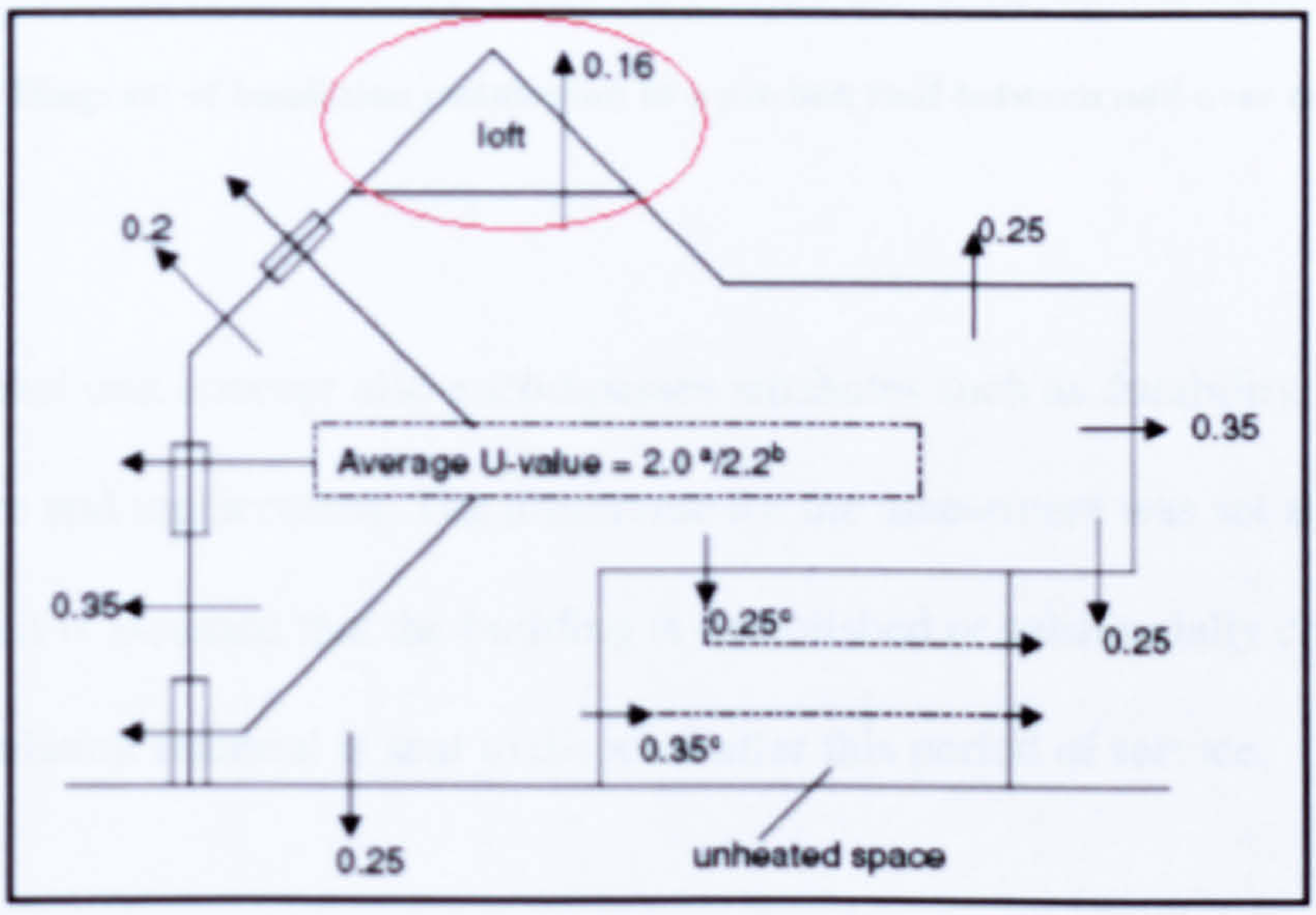


Figure 12 Summary of U values as outlined in Building Regulation Document Part L 2006

3.2 *The functional unit*

The functional unit (FU) of the LCA is the quantified performance of a product system for use as an essential reference unit for the study. The amount of a given product required to perform the insulation function will depend upon the specific material characteristics such as thermal conductivity, density, *etc.* in order to achieve the U-value (thermal conductance) of 0.16 W/m²K within the specified application. In this case the application is modelled on the insulation of a first floor ceiling of plasterboard suspended on timber rafters into an open roof void, shown in Figure 13.

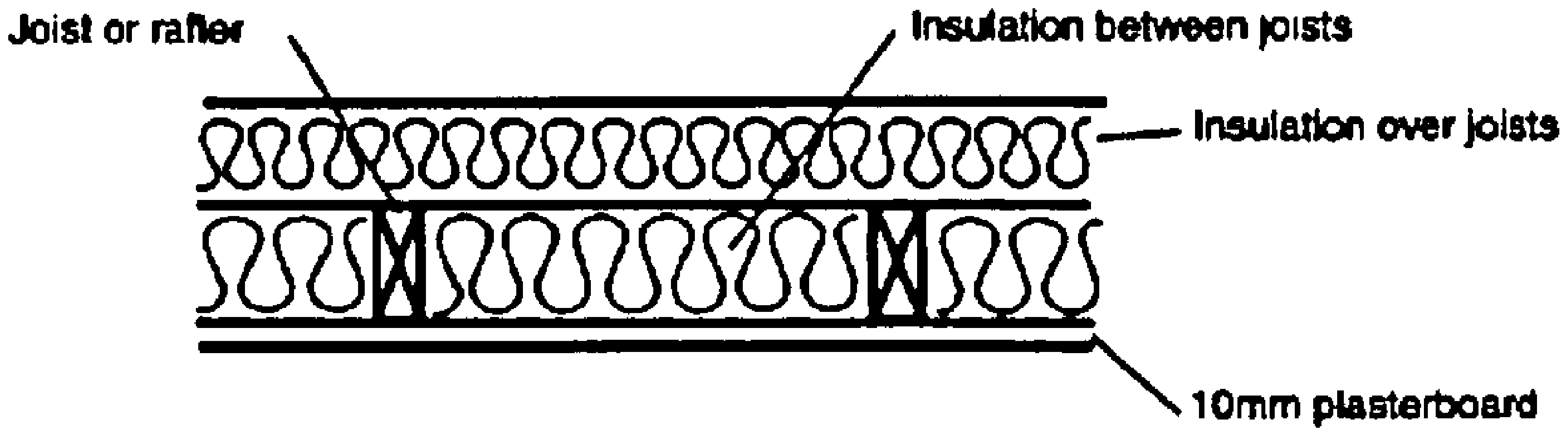


Figure 13 Diagram of insulation installation in a pitched roof between and over ceiling joists

The functional unit concept also encompasses attributes such as durability, stability, maintenance and replacement. The timeframe for the assessment was set at 60 years after which it is assumed that the building is demolished or substantially changed, so that the insulation material is sent to disposal after this period of service.

The Functional Unit for the study was for the insulation of one square meter within the cold roof space of a given dwelling described as:

"The manufacture, installation, use and disposal of an insulation material for one square meter of the central part of a first floor plasterboard/timber ceiling in a UK

domestic house to a U-value of 0.16 W/m²K for a period of 60 years service (Building Regulations Part L)"

The properties and quantities required to fulfil the FU for each unit of the insulation products being examined is presented below in Table 6.

Table 6 The reference flows for each insulation material required to meet the same functional unit of 1 m^2 of loft insulation to achieve 0.16 W/m²K

Product name	K value (W/mK)	Density kg/m^3	Thickness (mm) to achieve U-value	Functional Unit (kg)
Isonat	0.039	35	225	7.875
Thermafleece	0.039	25	225	5.625
Rockwool batt	0.037	32	200	6.4

3.2.1 Allocation procedures

Allocation is the partitioning of input or output flows of a unit process to the product system under study (ISO 14040). Allocation procedures are needed when dealing with systems involving multiple products or by-products. Allocation within this study was conducted on a mass allocation basis ***except where stated***. For example, the "environmental burden" carried by two by-products is split between them in the same proportion as the different masses of the by-products resulting from the given process. This was used as opposed to an assumed 50% split between two products or an ***economic allocation*** procedure where the proportion of burden would be split by the same proportion as that presented by the economic value of the products.

3.2.2 Impact assessment categories and methodology

The Institute of Environmental Sciences (CML) is an institute of Leiden University (The Netherlands) whose main area of work is research and education in the field of environmental sciences. Their Department of Industrial Ecology created the CML 2002 methodology which shows set baseline of environmental impacts. It is this base line that was used for general comparisons between the products studied arising from the life cycle impact assessment (LCIA) phase. The CML impact categories were used for general comparisons and their abbreviations and units used are as follows:

ADP = abiotic depletion (kg antimony eq.)

GWP100 = global warming on 100 year time-frame (kg CO_2 eq.)

ODP = ozone layer depletion (kg CFC-11 eq.)

HTP = human toxicity (kg 1,4-dichlorobenzene eq.)

FAETP = aquatic toxicity, Freshwater (kg 1,4-dichlorobenzene eq.)

TETP = terrestrial ecotoxicity (kg 1,4-dichlorobenzene eq.)

POCP = photochemical oxidant creation (kg ethylene eq.)

AP = acidification (kg SO_2 eq.)

EP = eutrophication (kg PO_4 eq.)

The definition of the 10 default impact categories of CML 2000 are defined by Guinée, et. al, (2001) as the following:

- **Abiotic resource depletion:** Non-living resources like minerals, coal or crude oil. The debate on the characterisation of depletion categories is not yet settled. In this method, characterisation is based on ultimate reserves and extraction rates. The unit of indicator result is kg of antimony equivalent.

- **Global warming:** This category refers to the impact of emissions on the atmospheric radiation heat adsorption, also known as greenhouse effect. Emissions are characterised as the global warming potential for a 100-year horizon. The units of indicator result for this method are kg CO_2 equivalent.
- **Stratospheric ozone depletion:** This refers to the deterioration of the stratospheric ozone layer that stops solar UV-B radiation from entering the atmosphere. The units of indicator result are kg of CFC-11 equivalent.
- **Human toxicity:** This category is related to the harmful effects of substances on human health. Emissions are characterised as human toxicity potential in an infinite time horizon, in kg 1,4-dichlorobenzene equivalent.
- **Ecotoxicity**: Ecotoxicity is divided into two categories depending on the environmental sub-compartment: freshwater aquatic ecotoxicity and terrestrial ecotoxicity. The ecotoxicity impact categories refer to the potential toxic effects of substances in the natural environment. Ecotoxicity potential is considered to happen on a global scale and an infinite time horizon. As such there is much debate over its importance and interpretation. For example a farm dependant product will often have a high apparent impact in these categories but this impact will be dispersed over a larger geographical region than a single factory outfall. Results are expressed in kg 1,4 dichlorobenzene equivalent.
- **Photochemical oxidation:** Also known as photo-oxidant formation. Sunlight causes some emissions like VOCs and CO, in the presence of NOx to form chemical oxidising compounds such as ozone. Photo-oxidant formation is also

known as summer smog. Characterisation results are expressed in kg ethylene equivalent.

- **Acidification:** This category is related to the acidification of the environment by pollutants such as SO_2, NOx and NHx. These emissions react with water in the atmosphere and form acids that have several effects on the natural and man-made environment. Emissions are characterised as the acidification potential in kg SO_2 equivalent.
- **Eutrophication:** When there is an excess of nutrients in the environment, shifts on species distribution and excessive production of biomass may happen. Due to the use of fertilizers farm based products are often perform badly in this category however it is worth noting that all farm practice has to adhere to strict regulations and its impact is geographically dispersed. This category characterises emissions of nutrients such as N and P into kg PO_4 equivalent.

3.2.3 Normalisation

Although normalisation is an optional element of LCA, it can show to what extent an impact category has a significant contribution to the overall environmental problem. It compares the absolute score for impact in each specific category with the profile of an average Western European citizen's emission in that category in the giver year (Tho, 2005). Normalisation was used within the study to provide perspective to the scale of environmental impacts reported.

3.2.4 Data quality requirements

Detailed information such as processing data was obtained from respective manufacturers of Isonat, Thermafleece, Rockwool and their suppliers where possible. The manufacture and disposal of common elements within the ceiling/loft unit have been excluded from the assessment (*e.g.* ceiling joists, plasterboard). As far as possible, primary data describing the quantities of materials, co-products, by-products and wastes and emissions from current processes for insulation material was obtained directly from manufacturers. In the case of the NFIs this was largely as disaggregated unit process data obtained in co-operation with the manufacturers and their suppliers. In the case of the Rockwool material, these were aggregated cradle-to-gate whole system datasets taken from the report by Schmidt *et al.* (2003).

3.2.5 Assumptions and Limitations

Systems were compared using the same functional unit and equivalent methodological considerations, such as performance, system boundaries, data quality, allocation procedures, and decision rules on evaluating inputs and outputs and impact assessment. The following specific assumptions will be used:

- The meaning of "Loft" in this report is that of a ventilated space with exposed ceiling joists and no boarding.
- The roof was assumed to be a "cold" roof *i.e.* one where the insulation is not attached to the inside of the sloping roof but laid directly between and over the under-story ceiling joists.

- The loft ceiling joists assumed were set at 150 x 50 mm, evenly spaced at 400mm centres - , 140 mm thick roll insulation can be fitted into the space between the joists equally and a further 100 mm roll placed cross-hatched on top of the joists
- The study area was 1m square, 400 mm in width between joists (different thickness may be required for different types of insulation materials)
- It is assumed that there was no need to clear spaces around, cables, light fittings, and beneath the water tanks in the 1 m^2 studied.
- No pins or sheets were needed.
- No compression of the material was allowed
- Service life for insulation material was 60 years

Further assumptions and limitations made regarding the individual products studied are discussed in the data collection section later in the report as part of each product's discussion.

3.3 LCA Inventory Analysis

The life cycle inventory analysis is a process of quantifying energy and raw material requirements, atmospheric emissions, waterborne emissions, solid wastes, and other releases for the entire life cycle of the product.

3.3.1 Data Collection Process

In general the data collected for the natural fibre based products were, where possible, collected through direct contact with the manufacturer in the form of site visits and personal communications. The data collected from the conventional insulation material manufacturers were based mainly on a previously conducted LCA that had been commissioned by the company studied.

3.3.1.1 Primary data

Primary data regarding the products studied were in general obtained through consultation with manufacturers. An initial questionnaire was sent out to all manufacturers concerning insulation production process with data on: proportion and origins of main raw materials and co-products, by-products, transport types and distance, energy used, manufacturing process; location of production and manufacturing and dimensions of the products in available sizes. The data collection process is summarised below.

- **Thermafleece** – Primary data regarding Thermafleece were obtained from Christine Amstrong at Second Nature Ltd, Neil Sagar and Tim Whitaker at Haworth Scouring Company and Carl Rushton at John Cotton Manufacturing.
- **Isonat** – Primary data regarding the Isonat product were obtained from; Gary Newman at Plant Fibre Technologies, Jean Pierre Buiton at Buitex, and Mike Duckett at Hemcore.
- **Rockwool** – Life cycle inventory aggregated data on Rockwool batt from the report by Anders Schmidt *et al* (2003)

3.3.1.2 Secondary data

It was not possible within the scope or resources of the study to acquire site-specific primary data for all unit processes involved within the system boundary for the products. As such, where data gaps existed, generic data and on occasion surrogates within a recognised database were used and referenced accordingly.

The databases or libraries within SimaPro version 6 include BUWAL 250 Library (written by Pre Consultans in the Netherlands) which has been used for transport and Disposal scenarios, and Ecoinvent data (written by the Swiss Centre for Life Cycle Inventories) that has been used for all other processes and materials. They are both internationally recognised datasets and represent data based mainly on general EU or UK specific pollution. These have been used as it was understood that they were the most thorough data available in the respective areas they have been used, thus a good substitute for first hand collection of emissions data that could not be collected due to the projects time constraints. A separate independent database was used for a potential

PLA (Polylactic acid) based binder that written by Gareth Davies of Imperial Collage London using SimaPro version 6 and its database libraries.

It is noted that the use of secondary data can be problematic. It has not been written for the particular product studied and will thus have its own system boundaries that may extend far beyond what is required. As such, the secondary data concerning larger impacting materials or processes was analysed to see what was included and if their impacts were relevant to the study.

3.3.2 Isonat

A description of the inventory for Isonat is given below: The carbon content of hemp fibre is taken as 45.7% on a dry mass basis (Energy research Centre of the Netherlands, 2007)

3.3.2.1 Hemp Farming

The hemp for the product is grown in the south east of England for primary processing at Hemcore, Near Bishop's Stortford, Hertfordshire. 70% of the crops are Currently grown within 100 km of the factory, generally in East Anglia, whereas the final 30% is grown an average of 190 km away elsewhere across the UK. The farming of UK hemp requires the following stages, this methodology has been built up as an average process utilized by the majority of the supplying farms.

After the previous crop has been harvested the field is de-cultivated with a 4m wide deep cultivator. Prior to sowing, the ground is then sprayed with 3 l/ha of Round Up, a glyphosate based contact herbicide, from a 24 m wide boom sprayer. The crop is then sown using a 4 m wide combination drill and then rolled with a 9 m wide roller. The crop is then fertilized with NPK fertilizer with a formulation that provides on average 100 kgN/ha 30 kg/ha P and 30 kg/ha K from a 24 m wide boom sprayer and left to grow. The amount of P and K fertilizer varies between farms but in general usage is very low, just sufficient to maintain levels in soil. Depending on soil type none may be used for at least three years (Duckett, personal communication). At the end of the growing season the crop is then harvested using a 6m wide forage harvester and then tedded, *i.e.* spread out to dew ret, with a 6 m wide tedder. The retted crop is then raked up, square baled (both 6 m wide) and then stored on farm before being transported to the factory by lorry or by tractor and trailer in cases where the farm is particularly near the factory. The 550 kg delivered bales require 289 g of polyester twine. As an average and reliable figure each farm yields around 6 tonnes dry straw per ha (Duckett, personal communication).

It was found that there were some discrepancies between the best available secondary data used and the actual on farm processes. For example many of the Ecoinvent farm processes based on Swiss farming methods assume much smaller machinery than that used on the comparatively large scale hemp farming in East Anglia. For example the de-cultivating process used assumes a 2.5 m wide cultivator rather than a 4m wide cultivator. The temptation to reduce the process to 62.5% was not however put into place. Even though it could be assumed that the larger scale farming is probably more efficient, the use of larger machinery will also add other impacts. Because no satisfactory factor could be devised, the farming processes where left unaltered. It was not thought to be worthwhile to look in to this matter further as farming in general had a relatively low impact on the overall product LCA.

3.3.2.2 Primary Processing

The primary processing carried out by Hemcore removes the shive, dust and any other major impurities from the harvested hemp straw and produces a baled fibre for transporting to France. This process involves a bale opener followed by a schutcher type decorticator and separator, from this the fibre is air cleaned to remove any further dust. The clean fibre is then baled using 774 g of wire per 100 kg bale and sold to Buitex. It is transported 872 km by road and 40 km by ferry across the English Channel, to Buitex in Cours le Ville, France in 25 tonne trucks.

The Shive fraction is sold once bagged and put on pallets. The dust is currently taken away and mixed with chicken manure and used as a fertilizer. In the future it is possible that it could be compacted into briquettes and sold as a fuel source. The total energy used in the factory is 810 kWh at an average through put of 1.5 tonne/h of hemp straw (at an average of 16% moisture content). During the current process there is nothing major replaced regularly, only the occasional knife sharpening which is not included in this analysis.

3.3.2.3 Insulation Manufacture

At Buitex the fibre is blended with the recycled cotton fibre, a bi-component polyester fibre and a fire retardant then air laid and bonded to produce the Isonat Product the details of which are presented here:

The UK hemp fibre is initially dipped in a solution that contains the fire retardant and then dried. The fire retardant is an ammonium phosphate based material purchased from THOR in Germany. The material is most likely to contain mono and poly phosphates but the exact European formulation is not possible to obtain (Nelson, personal communication). The fibre is then blended with the recycled cotton fibre and the bi-component polyester fibre. The blended fibre then goes through the process of air laying, thermal bonding and then trimming and packaging, with the waste trimmings re-blended in to the blending process. The cotton fibre is purchased from the local textiles industry and transported around 5 km in the form of wire bound 100 kg bales. The bi-component polyester is currently purchased from Korea, where it is shipped approximately 25,000 km to Marseille and transported 400 km to Cours la Ville by truck. It is packaged with one wrap of 100 g/m^2 of PP per bale. The 0.56 g of PP/kg of fibre is shredded and used in other products within the factory. The 5% by weight of dust that is removed during the manufacture is compacted into briquettes and given away for domestic heating. The final Product is packaged using 3.5 kg/m^2 of finished product of polyethylene plastic wrap and placed on wooden pallets before being shipped back to the UK on 25 tonne trucks.

The initial drying of the fibre after the fire retardant is added and the thermal bonding are possibly the most energy intensive parts of the process as together they require 2.32 kWh/kg of finished product of piped gas, whereas the whole factory uses only 0.15 kWh/kg of finished product of national grid electricity. There is generally no replacement of any parts required.

3.3.2.4 Summary of Input data

A summary of all data for the materials and processes (Table 7) and transport (Table 8) for the Isonat product is presented below.

Table 7 Materials and processes in the Isonat system studied – 1kg basis except for straw production where a 1 ha (6ton) basis is presented

Process name	Value	Unit	processes/materials involved	Value	Unit
Isonat production at Buitex, France	1	kg	Hemcore Hemp fibre production	0.35	kg
			Cotton fibres recycled 100% carbon	0.35	kg
			Bi component Polyester	0.15	kg
			Flame retardant (amonium phosphate based)	0.15	kg
			paper, unbleached	0.00001	kg
			Polyethylene, HDPE, granulate	0.028571	kg
			Extrusion, plastic film	0.028571	kg
			Electricity/heat		
			Electricity, high voltage, production France	0.15	kWh
			Heat gas	2.32	kWh
			Waste to treatment		
			Steel waste	0.008463	kg
			Packaging waste, paper and board	0.00001	kg
			Plastic waste	0.00084	kg
			Plastic waste	0.028571	kg
Bi component Polyester	1	kg	Polyethylene terephthalate, granulate, amorphous	0.5	kg
			Polyethylene terephthalate, granulate, bottle grade	0.5	kg
			Extrusion	1.5	kg
			Polypropylene, granulate,	0.00084	kg
			Extrusion, plastic film	0.00086	kg
Cotton fibres recycled 100% carbon	1	kg	**Electricity/heat**		
			Electricity, medium voltage, production	0.0125	MJ

			France		
			Heat diesel	2.5	MJ
			ECCS steel 50% scrap	0.004232	kg
			Emmisions to Air		
			Carbon dioxide	-1.47	kg

Hemcore Hemp fibre production (29%)	1	kg	Hemcore Farming hemp straw production	3.448	kg
Shive co-product (66.7%)	2.3	kg	steel 50% scrap	0.004232	kg
Dust co-product (4.3%)	0.15	kg	Electricity, medium voltage, GB	1.862	kWh
			Polyethylene, HDPE,	0.002	kg
(% Economic Allocation)					
			Waste to treatment		
			Plastic waste	0.000173	kg

Hemcore Farming hemp straw production	6	ton	Tillage, rotary cultivator	1	ha
			Application of plant protection products by field sprayer	0.625	ha
			Sowing	1	ha
			Haying, by rotary tedder	1	ha
			Haying, by rotary tedder	1	ha
			Baling	8.57	p
			Combine harvesting	1	ha
			Tillage, rolling	1	ha
			Polyethylene, HDPE, granulate	-8.57	kg
			Extrusion, plastic film	-8.57	kg
			Ammonium sulphate, as N, at regional storehouse	100	kg
			Ammonium nitrate phosphate, as P2O5	30	kg
			Potassium chloride, as K2O	30	kg
			Polyethylene, LDPE, granulate	0.000173	kg
			Emissions to air		
			Carbon dioxide	-10.054	ton

Table 8 Transport data in the Isonat system - functional unit (p) basis

Process name	Value	Unit	processes/materials involved	Value	Unit
Transport - Cotton fibre to Buitex	1	p	Truck 28t	0.0175	tkm
Transport - fire retardant to Buitex	1	p	Truck 28t	0.07	tkm
Transport - hemp fibre to Buitex	1	p	Truck 28t	3.052	tkm
Transport - hemp straw bales to Hemcore	1	p	Sea ship	0.14	tkm
			Truck 28t	0.35	tkm
Transport - Isonat to Coventry	1	p	Sea ship	0.35	tkm
			Truck 28t	8.75	tkm
Transport - PE fibre to Buitex	1	p	Truck 28t	1.4	tkm
			Sea ship	32.8	tkm
Transport - waste wire from Buitex	1	p	Truck 28t	1.75	kgkm

3.3.3 Thermafleece

The inventory of the Thermafleece product is given below: The carbon content of wool is taken as 50% on a mass basis (Roche, 1995).

3.3.3.1 Farming

A ***mass allocation*** has not been used in the case of the fleece supplied from upland sheep farming. This is because the fleece used for insulation is categorised as a waste by-product from the main function of sheep farming for meat production and it is of extremely low economic value or possibly even of negative "value" due to the costs of disposal otherwise (Williams *et al*, 2006 and Armstrong, personal communication). Therefore on an economic allocation basis the sheep wool has been given a zero allocation and thus not included in the life cycle assessment for Thermafleece as the ***upstream*** processes of sheep farming is assumed to be 100% allocated to meat production and breeding stock maintenance.

3.3.3.2 Scouring

0.25 kWh of electricity, 0.8 kWh of gas and 5 litres of water per kilo of greasy wool were used during the scouring and rinsing process (Whitaker, personal communication). Raw wool is washed or scoured in tanks filled with hot water containing detergent to remove contaminants. The raw wool is passed through the first scouring bowl, then squeezed between rollers and carried into the 2nd bowl. It passes through four bowls until eventually it is rinsed in another bank of four bowls containing clean water. The Haworth facility can process 3.5 tonnes an hour of crossbred wool (Haworth Scouring Company, 1999), the equivalent to scouring the wool from 300,000 sheep a week. (Sagar, personal communication).

3.3.3.3 Bonding

In order to adhere the bicomponent polyester binder to the wool it is heated. Energy used during this thermal bonding stage is an estimated 0.58 kWh of electricity and 0.94 kWh of gas per kg of Thermafleece (Rushton, personal communication).

3.3.3.4 Summary of inputed data

A summary of all data for the materials and processes (Table 9) and transport (Table 10) for the Thermafleece product is presented below.

Table 9 Materials and processes in the Thermafleece system - kg basis

Process name	Value	Unit	processes/materials involved	Value	Unit
Manufactured Thermafleece	1	kg	Clean, Raw Wool	0.85	kg
			PP packaging film	0.0286	kg
			Bi component Polyester	0.15	kg
			Electricity/heat		
			Heat gas	0.94	kWh
			Electricity, medium voltage, production GB	0.58	kWh
			Emissions to air		
			Particulates, SPM	0.1	kg
			Waste to treatment		
			Plastic waste	0.0286	kg
Clean, Raw Wool	1	kg	Scouring, Rinsing and Cleaning	1	kg
			Polypropylene, granulate	0.00084	kg
			Extrusion, plastic film	0.00084	kg
			steel 50% scrap	0.004	kg
			Greasy wool	1.15	kg
			Waste to treatment		
			Plastic waste	0.00084	kg
			Steel waste	0.004	kg
Bi component Polyester	1	kg	Polyethylene terephthalate, granulate, amorphous	0.5	kg
			Polyethylene terephthalate, granulate, bottle grade	0.5	kg
			Extrusion	1.5	kg
Scouring, Rinsing and Cleaning	1	kg	Electricity, medium voltage, production GB	0.288	kWh
			Heat gas	0.92	kWh
			Fatty alcohol sulfonate, petrochemical	0.01	kg

			Borax, anhydrous, powder	0.085	kg
			Resource depletion		
			Water, process, drinking	7.14	kg
Greasy wool	1	kg	Polyethylene, HDPE, granulate	0.002	kg
			Extrusion, plastic film	0.002	kg
			Emissions to air		
			Carbon dioxide	-1.83	kg
			Waste to treatment		
			Plastic waste	0.002	kg

Table 10 Transport data for the Thermafleece system - Functional Unit (p) basis

Process name	Value	Unit	processes/materials involved	Value	Unit
Transport Clean Raw Wool to Factory	1	p	Truck 16t	0.037	tkm
Transport Fleece to Scouring	1	p	Truck 16t	1.19	tkm
Transport of Binder	1	p	Sea ship	3.61	tkm
			Truck 28t	0.47	tkm
Transport of PE fibre	1	p	Sea ship	14.07	tkm
Transport thermafleece	1	p	Truck 16t	1.28	tkm
Scouring, Rinsing and Cleaning	1	p	Truck 28t	0.00001	tkm

3.3.4 Rockwool

It was also not possible to conduct a full site data collection for the Rockwool insulation product. As such the data for the Rockwool product used here was based entirely on a previous LCA conducted by Anders Schmidt of dk-Teknik Energy & Environment on behalf of Rockwool (Schmidt *et al*, 2003). The data was provided in the form of an aggregated data set. However from the body of the report the following points of interest have been extracted:

- The Rockwool Product is 77% virgin raw material in the form of diabase, Gotland stone, limestone, cement and bauxite. The remaining 23% are classed as waste materials (from various activities): white dust (cement production), slag (steel production), aluminium silicate (steel foundry), returned stone wool and recycled material from other Rockwool production sites. The proportions of these materials in the final product are not known.

- The production of Grodan (17%) and briquettes for other Danish production sites (29%) is subtracted from the total energy used through co-product allocation.

- There was a reported 10% difference (loss) from input to output in the inventory. This has been attributed to evaporation of water and loss on ignition and "non-specification densities".

3.3.4.1 Raw material acquisition

- It was assumed that diabase, Gotland stone and lime stone all required 0.06 MJ/kg for their extraction. Bauxite extraction was assumed to consume about 2.56 MJ/kg of primary energy and the cement fraction 3.67 MJ/kg in coal, LPG and electricity.

- Form oil was estimated to use 40 MJ crude oil per kg, though it is only used in small amounts of briquette production *i.e.* 0.026 kg/kg briquette.

- No environmental burden was placed on the waste materials other than that of transport. The energy used to re-melt the materials was included in the overall energy inventory.

3.3.4.2 Briquette production

From a public report issued by DEFRA (n.d.) the following additional information has been shown regarding the whole UK production plant:

- The melting and fiberising stages of production account for the bulk of the energy consumption in roughly equal proportions, totalling about 70% of consumption, with a further 15% coming from the cooling and curing stages.

3.4 Life Cycle Impact Assessment Phase (LCIA)

The diversity of possible end of life scenarios for all the products, make direct comparisons difficult. Thus for reasons of simplicity the results from the LCAs are first shown here for the ***cradle to installation*** part of the analysis only, *i.e.* the whole production process and transport functions used for each product studied from raw materials to delivery to the study house. This a natural and equal cut off point for all the products studied and is not thought to introduce any bias and indeed the results of the full ***cradle to grave*** analysis are presented and discussed later in this chapter in the end of life Section 3.5. The environmental impacts using the CML 2 Baseline v2.1 method were calculated from the imputed data as previously described. They are presented for both NFI products on a ***cradle to installation*** basis on both a ***Functional Unit*** basis (in Table 15) and on a ***per kg*** basis (in Table 16) in the Appendix.

It must be noted that only with a ***great deal of caution*** and the understanding of what is included in each set of data should the data presented here be used for any comparisons with external data. The data presented in the generalised results section here and in the Appendices should only be compared to data analysed with comparable system boundaries and assumptions.

3.4.1 Generalised results

The results from the LCAs of all products studied on a ***cradle to installation*** basis are presented in the form of a graph in Figure 14 below using the previously described CML baseline to present a wide selection of environmental impacts on one graph.

The data is then show on a "normalised" basis in Figure 15 to give a sense of perspective to the generalised results. In this case the data presented is normalised against the impact of "the average West European citizen".

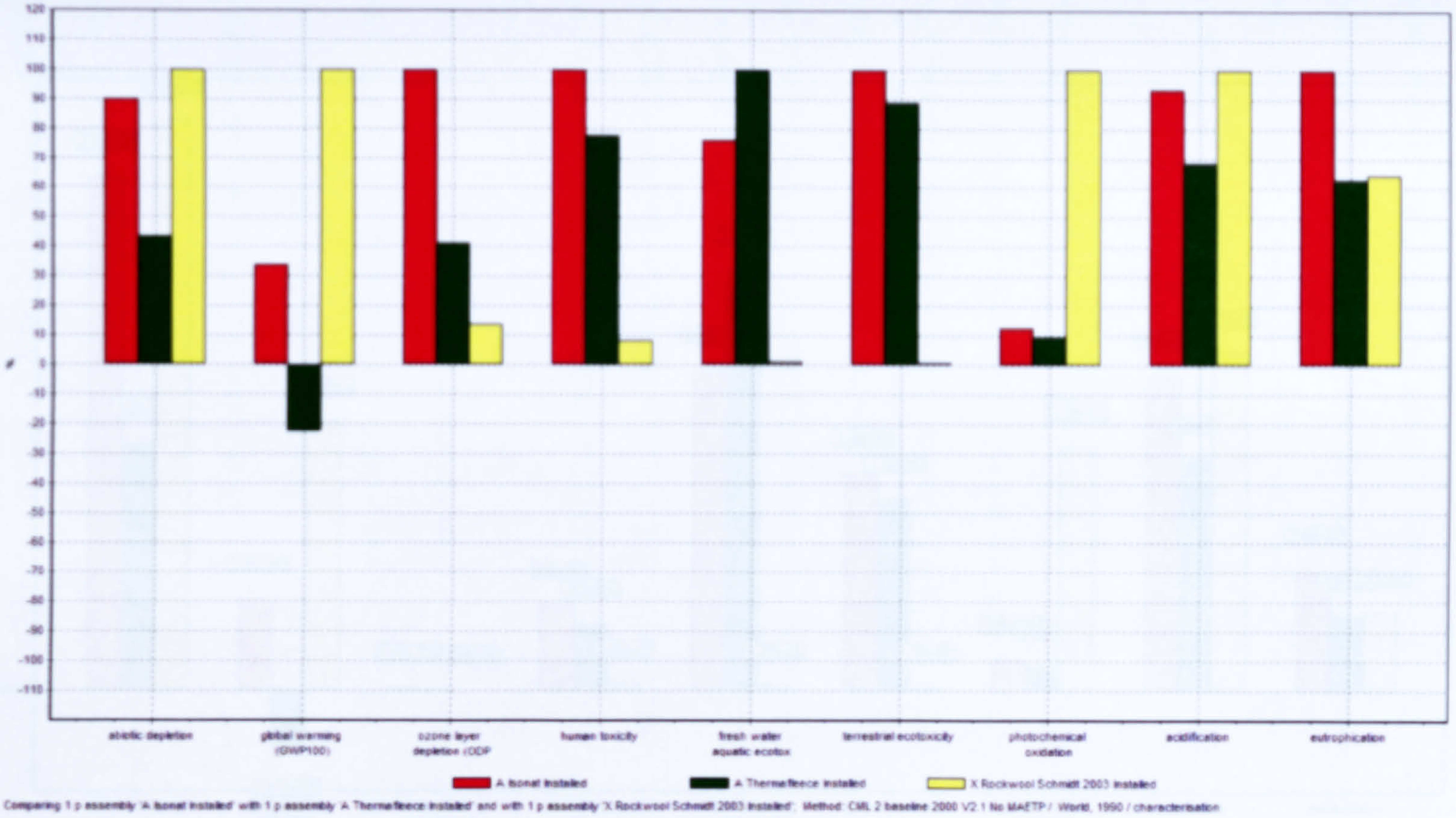


Figure 14 Graph for comparison of NFC and conventional insulation material environmental impact using CML baseline

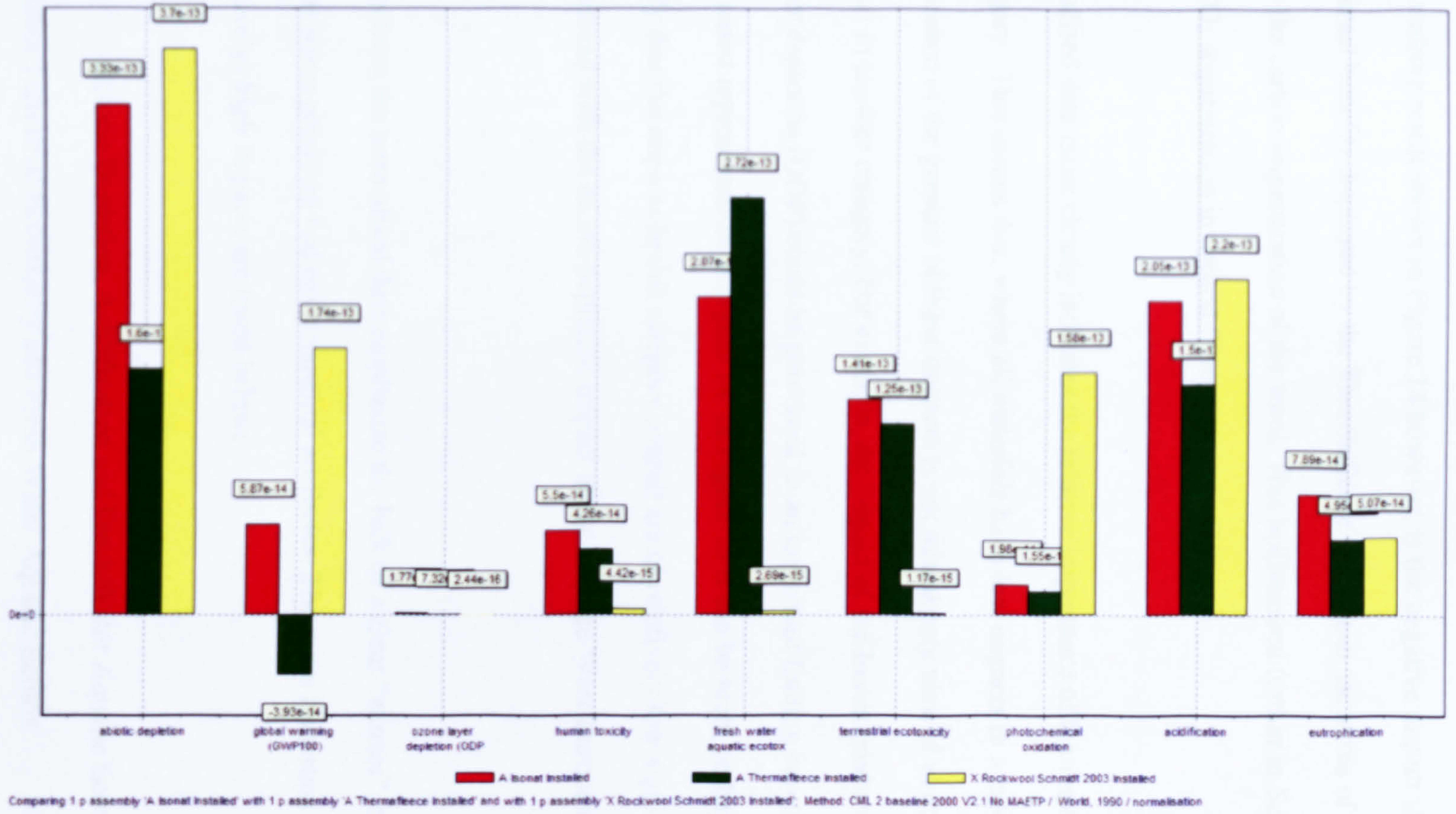


Figure 15 Graph for comparison of NFC and conventional insulation material normalised environmental impact using CML basline

A general result from Figure 14 is that there appears not to be a clear "winner" or "loser" in terms of overall environmental, impact this is emphasised further in Figure 15 where the same results have been normalised.

One very striking result shown in Figure 14 however, is the negative impact (*i.e.* environmental benefit) displayed by the Thermafleece product in the terms of GWP caused by the carbon sequestration of the wool. This is discussed further in Section 3.4.1.1 (CO_2 sequestration in natural fibres) on page 118.

The normalised data more clearly indicates the relative importance of the impacts in each category. This means that, where all materials have low impacts in a category, the significance of the greatest of these impacts is not mistakenly viewed as equal to a high impact in another category. For example, the impact of the Isonat product in ozone layer depletion (ODP) could be perceived as an important finding based on the non-normalised representation in Figure 14. In Figure 15 it can be seen, perhaps more realistically that the impacts in this category overall are of relatively low significance when compared with the ozone-depletion impact of the average West European citizen.

The results from the normalised data emphasize the lack of a clear "winner", as each product has some good and bad environmental attributes. The more important (comparatively) ***high*** impacts are listed below:

Isonat	Abiotic Depletion, Acidification and Fresh Water Aquatic Ecotox
Thermafleece	Terrestrial Ecotoxicity and Fresh Water Aquatic Ecotox

Rockwool Abiotic Depletion, Acidification and Global Warming (GWP 100)

In a similar way to the use of secondary data, comparisons to aggregated datasets can be problematic. For example the Rockwool inventory provided does not appear to have any impact in any toxicology category. Due to the lack of detail available on the production of the aggregated dataset provided it is difficult to go into a more detailed comparison.

It is possible that some emissions, that may be relevant to various impact categories, were not reported in the inventory. For example phenol and formaldehyde emissions from the Danish factory are not reported in the inventory provided for this product. They do however appear in the Integrated Pollution Prevention and Control (IPPC) emissions data for the UK factory as a whole. It is understood that this may be due to differences in manufacture or emissions capture techniques between the two factories or that the emissions of phenol and formaldehyde only occur during the production of other materials. It is however surprising that no emissions are reported in by Schmidt *et al* (2003) given the use of phenol formaldehyde binders.

It is not in any way suggested that data points are omitted deliberately to mislead but it does highlight a difficulty encountered when interpreting aggregated data. When aggregated datasets are used, what is included within the system boundaries that produce the disclosed results are outside the control of the user. They can thus not be analysed to make sure a fair comparative system boundary is used for the other products under comparison. If the data has been abbreviated in any way to omit emissions that are seemingly insignificant to one study the use of this data may miss out an impact that is significant using a different functional unit. Also a small emission removed for simplicity in one dataset may then unrealistically show up as a limited impact when compared to other datasets where the emission is included. A further discussion of the use of aggregated datasets is presented in Chapter 4 as part of the sensitivity analysis (Section 4.2).

The Thermafleece product is nearly 30% less dense than the Isonat product. This low density requires less material and as such carries only a (proportional) fraction of the environmental burden of its materials and processes. As such it is a simple and effective method of reducing a product's environmental impact. Where LCA studies are reported on a per kilo basis this product advantage is not shown.

There are some products currently available that have very low densities, *e.g.* the Knauf Crown Loft Roll 44 with a density of 10 kg/m^3 which is 70% less than the Isonat product studied here (Knauf, 2006). Manufacturers other than Knauf do not produce such a low density product in general for fears that the lack of bulk will result in the product sagging over time and thus reduce its thermal insulation properties. It is not possible to say whether any of the products studied here or the Knauf product would do this or indeed to what extent, as there is no reliable data available on the performance of the products studied.

This presents an important issue regarding the assumptions made in this study. Peuportier (2001) stated that a 25% variation of the conductivity, *i.e.* from 0.04 to 0.05 W/(m K), lead to a 2.4% increase of the heating load and a 2.3% increase of the overall CO_2 emissions over the 80 year period considered. A whole 25% reduction in conductivity is perhaps unlikely to occur just from an occurrence of sagging except perhaps in severe cases. However a mineral wool insulation product is able to save over 100 times more energy than is used in its production compared to a non-insulated loft (Rockwool Ltd, 2006). A 2.4% increase in heating load due to any sagging therefore would be equivalent - in energy consumption terms - to more than a 200% increase in the energy needed to produce the insulation. This would represent a substantial difference between the insulation products and highlights the potential importance of the assumption made that insulation performance is unchanged over the 60 year lifetime modelled. As such future studies in this area are recommended.

3.4.1.1 CO_2 sequestration in natural fibres

GWP impacts in general stem from the use of carbon emitting fuel sources and are thus linked to the energy consumption of most products. It is however noted that although the GWP reported for the natural fibre products is far lower than that of the conventional material, the energy requirements are actually higher (presented in Table 11 below).

Table 11 the total energy requirement (calculated using the Ecopoints 97 V2.1 method) and the GWP (calculated using the CML 2 baseline 2000 V2.1) for the studied products

Impact category	Unit	Isonat	Thermafleece	Rockwool
Energy	MJ LHV	263	207	140
Global Warming (GWP100)	kg CO_2 eq	2.72	-1.82	8.03

For the natural fibres, the lack of a simple coupling between the energy consumption to make the product and its Global Warming Potential is a result of the removal of CO_2 from the atmosphere via photosynthesis. This occurs during its conversion within the plant into the ligno-cellulosic fibres and other components of the plant body. In the case of sheep wool, the carbon sequestered by plants goes through a further conversion step in the animal into the proteins of wool. Thus, the sequestration of atmospheric CO_2 into the basic raw material in the natural fibre products exerts a strong 'negative' GWP effect (removal of CO_2 from the atmosphere). In the case of Thermafleece (and many other renewable materials), this is of sufficient magnitude to more than counterbalance the GWP emissions from energy consumption in the manufacture of the product.

Two critical components in assessing the overall GWP balance over the life cycle of natural fibre materials and products is 1) their longevity in use (in this case assumed to be 60 years in a building) and 2) the end-of-life disposal method. It is in the disposal phase of the life cycle that some, or all, of the carbon sequestered into the product may be returned to the atmosphere, this being highly dependent upon the specific disposal route followed. This is reported in the end of life section that follows.

3.5 End of life scenarios

As mentioned previously there are many end of life scenarios for each of the studied products after the 60 year in-use period. During this assumed 60 year in-use period it is highly likely that legislation surrounding the disposal of construction waste will be changed and as such it is very difficult to assume one particular scenario will be used (Roberts, personal communication). A range of potential scenarios are displayed in Figure 16 with the selected studied scenarios shown in blue. These scenarios have been selected to provide a representative display of the effect the different scenarios have on the LCA as a whole rather than a prediction of the most likely scenarios.

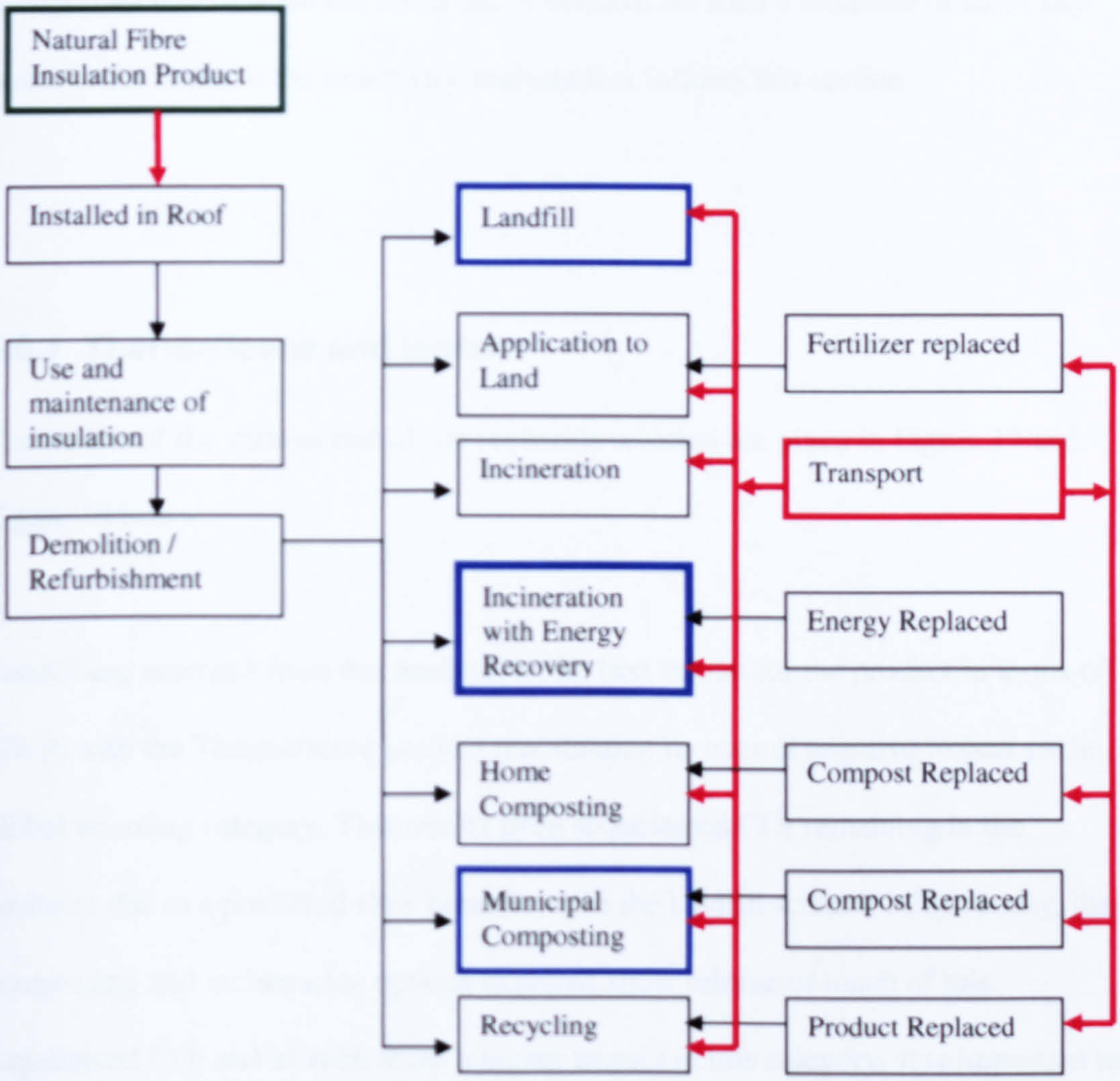


Figure 16 Flow Chart to display potential End of Use Scenarios for the Natural Fibre Insulation Materials with individual scenarios selected for further study highlighted in blue

3.6 End of Life Scenario Analysis Results

What follows is a study of the selected of end of life scenarios and their effect on the over all life cycle impact of each product. As with all results displayed in this report it is important that they are not taken out of context. As such a selection of these key issues is discussed in the sensitivity analysis that follows this section.

3.6.1 Thermafleece and Isonat

The results of the various end of life scenarios selected are given in Figure 17 and Figure 18 below.

Landfilling emerged from this analysis as the best option for the product in terms of GWP, with the Thermafleece product maintaining its overall negative impact in the global warming category. This results from sequestered CO_2 remaining in the products due to a predicted slow breakdown in the landfill scenario. Conversely, the composting and incineration options explored show release of much of this sequestered CO_2 and as such show a higher impact in this category. It is important to note that not all of the sequestered CO_2 is released by the composting scenario as the final compost product (containing around 50% of the original material's mass), will still retain a portion of the sequestered CO_2.

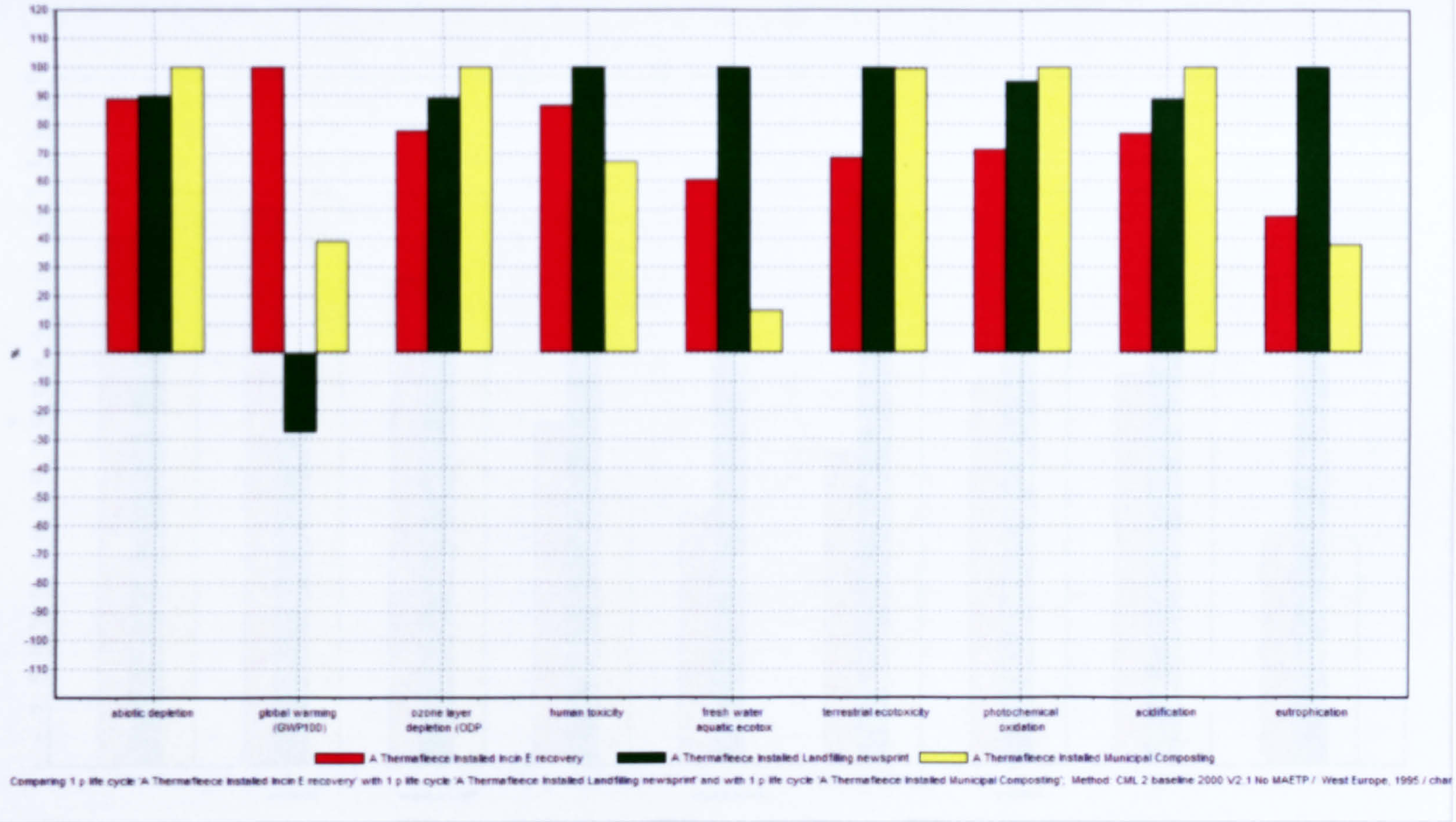


Figure 17 The results of the varied end of life scenarios selected on the Thermafleece product

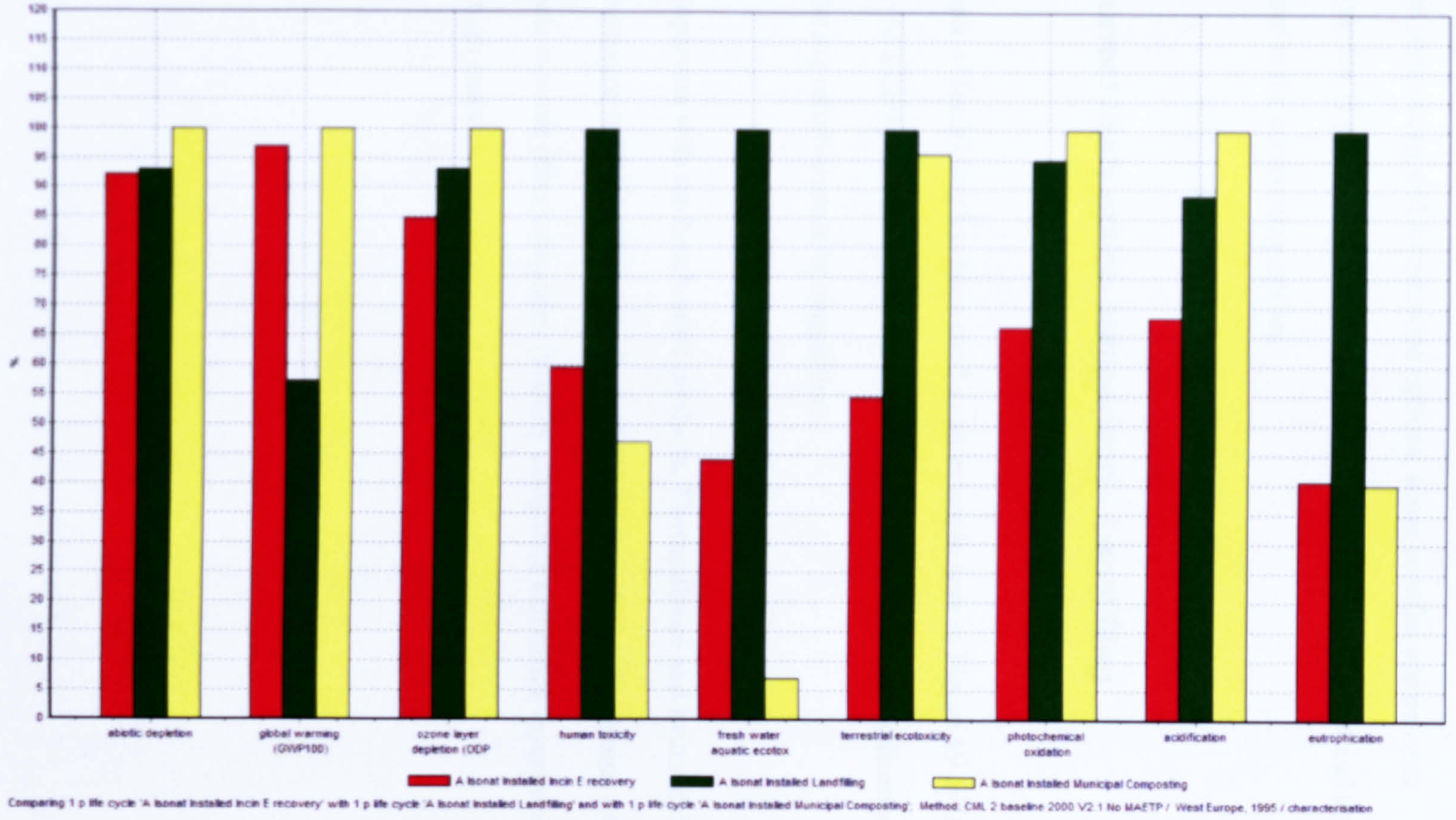


Figure 18 The results of the varied end of life scenarios selected on the Isonat product

In most other categories the impacts are relatively similar for the examples chosen, except for eutrophication and fresh water aquatic ecotoxicity where the landfilling option presents a comparatively larger impact.

Within the composting and incineration options, some benefits accrue from substitutions for 1) grid electricity generation in the incineration option and 2) peat replacement in the composting option.

3.6.2 Current likely option comparison – Landfilling

The example of landfilling has been used as an example here in Figure 19 as it is thought to be a likely current option for an insulation material removed from a building during refurbishment or demolition.

In this comparison with the bench mark products, Thermafleece and Isonat deliver good performance in Global Warming Potential. It is also shown that Isonat exhibits high impacts in some other categories (toxicity categories and ozone layer) primarily due to its high mass.

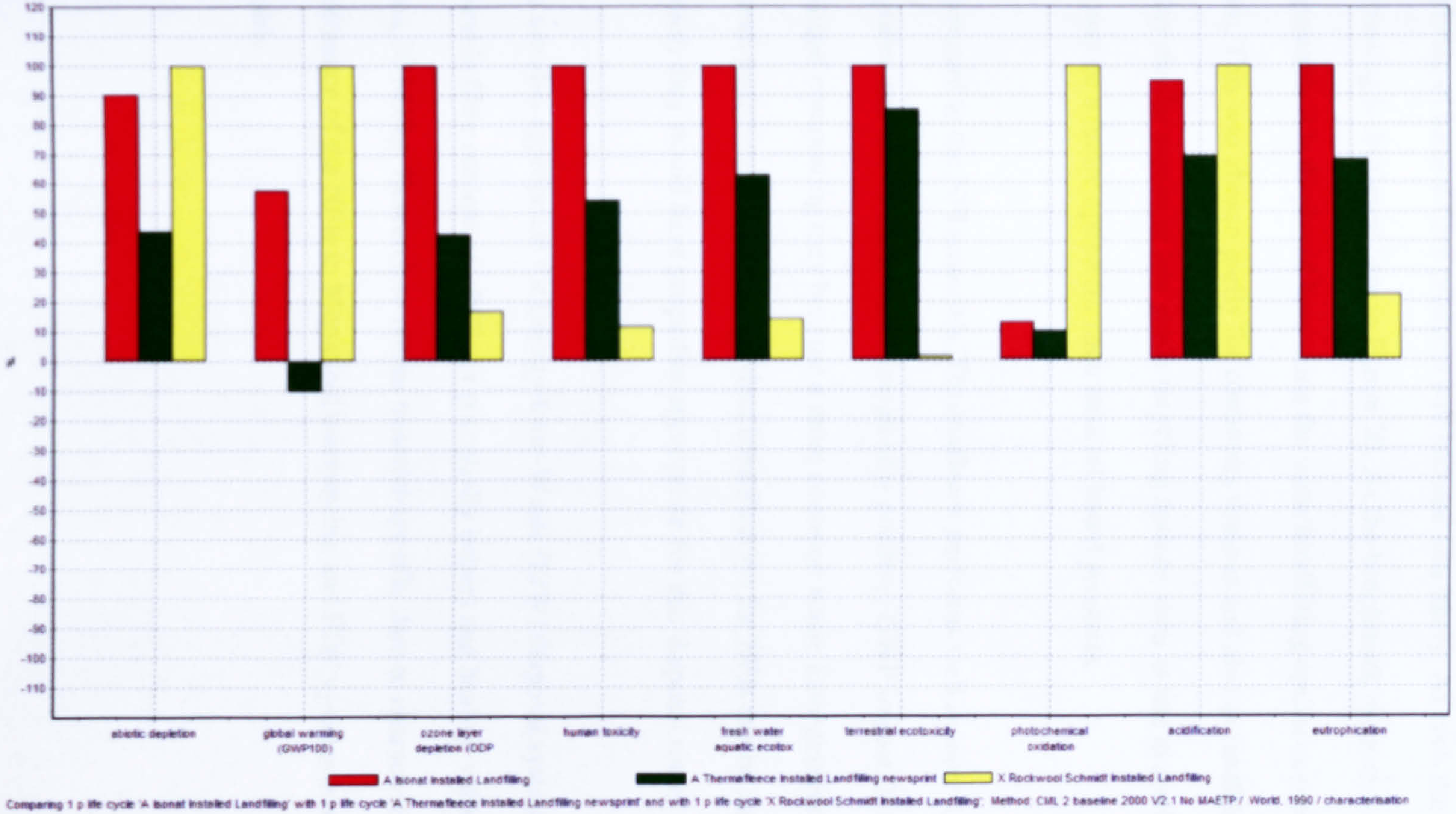


Figure 19 the results of a comparison of NFIs with benchmark product with a landfilling disposal scenario

3.6.3 Example future option comparison – Composting

It is assumed here that as legislation progressively restricts total landfilling, the landfilling of natural fibre products will become less likely. As such the option of composting is displayed here in Figure 20. As the benchmark product is not compostable it is displayed here using the same landfilling option as previously shown. This was chosen partly for continuity reasons and also as landfill is believed to display similar results to low grade recycling options such as use in road surfacing that may be a future option for such mineral based products.

With regard to the NFI materials, Thermafleece performs well in most impact categories and shows the lowest (though now positive) GWP impact. In the future, municipal composting may become a more common waste management system in the UK and, assuming that reliable product identification for NFIs can be achieved upon disposal, they would have properties appropriate for this disposal route.

NFIs are also appropriate for Energy-from-Waste (EfW) disposal systems with a renewable fibre content of ~85% (or potentially better) and heating values likely to be approx 20 MJ/kg. Research to obtain material-specific data to characterise the performance of the NFIs in Municipal composting and EfW systems would be valuable.

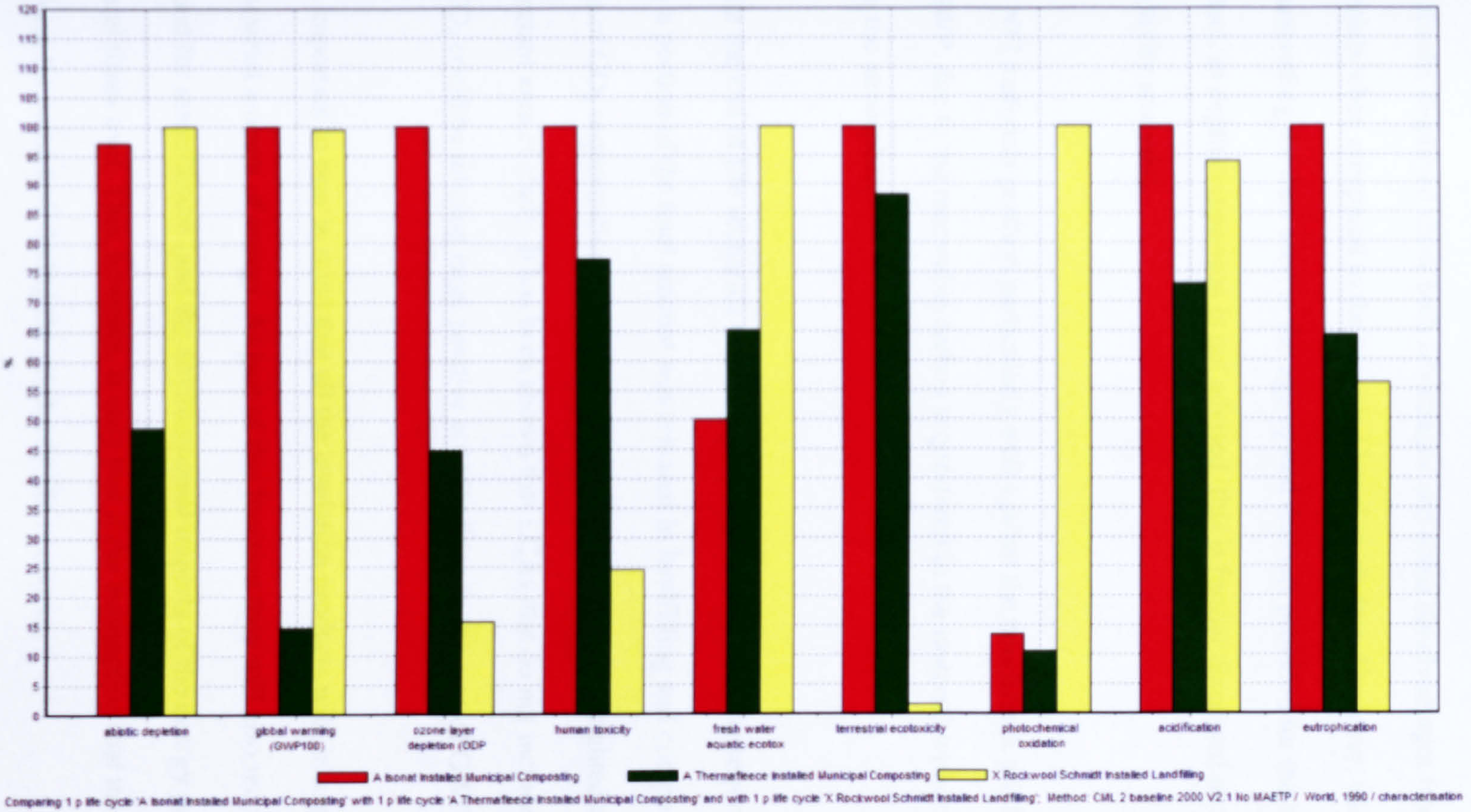


Figure 20 Example of a possible future disposal option, showing composting for NFI products and landfilling for benchmark products.

3.7 Conclusions from Benchmark Results

The results displayed show both advantages and some disadvantages from the NFI materials when compared to the provided benchmark data. However, without fully understanding the data used in the aggregated datasets provided for the benchmark product, in depth comparison is not advised (this is further discussed in the following sensitivity analysis).

The NFI materials perform particularly well against the benchmark product in terms of GWP, due to the renewable carbon sequestered in the material withdrawing CO_2 from the atmosphere.

While the end of life scenarios studied did show a release of some sequestered CO_2, only a portion of the total amount was released in landfilling and composting. The issue of CO_2 sequestration in renewable materials has been highlighted as an important area of study. It has been shown that LCAs that do not include this quantity of CO_2 could be missing large positive contributions in the area of GWP.

It is important to bear in mind that all the insulation products will, in use, save a substantial amount of energy. As part of this function they will also recoup the energy needed for manufacture (and the environmental impacts of the energy production) several times over. This, however, is only true if the assumption that they will perform the same task during the product's life is correct.

The issue of a product sagging and thus reducing the products thickness and thermal insulation property has been highlighted as a functional property that would benefit from further work and information. The reason for this is that any small change in the product's performance will affect heat and thus energy loss from the studied dwelling. Throughout the product's service life this could, if it is a variable property between different insulation products, have a much more significant effect than the initial production energy and, as such, alter the product's overall life cycle impact. This aspect of functional performance over an extended time period of decades could not be examined in depth due to a paucity of information – the study is therefore based upon an assumption of no change in insulation performance over the 60 year *in situ* period modelled. Research into the issues regarding the long term performance of insulation products *in situ* will be valuable to develop more accurate, comparable LCAs.

One notable characteristic of natural fibre materials is that of water sorption. This may affect their performance over the 60 year *in situ* performance studied here, especially when considering the heat released due to moisture adsorption and heat absorbed during moisture desorption. This for example, could have a significant impact over the lifetime of an insulation product if the quantities of heat energy involved are found to be significant.

4 Interpretation of Results

4.1 Introduction

This chapter completes the LCA analysis of the studied materials by means of Interpretation *i.e.* the fourth phase of the LCA study, as described in the ISO 14040 guidelines. The Life Cycle Impact Assessment phase in Chapter 3 showed that currently produced natural fibre insulation materials are comparable in their environmental profile to a conventional material dataset. A study of the data used, in comparison with other existing data sets, is described here in the sensitivity analysis. For the natural fibre products, the major impacting processes and materials are identified in the following marginal analysis. This area of study reveals the potential areas of improvement for the products and a further study of their suggested near future optimization shows a potential for lower environmental impacting materials.

4.2 Sensitivity Analysis

4.2.1 Secondary dataset usage

As previously mentioned it was not possible to alter the data for the Danish Rockwool product to include the UK emissions from electricity due to the aggregated nature of the data presented in Schmidt *et al* (2003). As such the emissions for CO_2 for example will be lower than if the same product was produced in the UK. *i.e.* 1 kWh of electricity production in Denmark (in 2004) produced 308 g of CO_2 as opposed to 467 g in the UK (International Energy Agency, 2006).

Data from Ecoinvent and other inventories have been used in the preparation of the natural fibre insulation material inventories. The Ecoinvent datasets act to accumulate certain impacts, for example in the toxicity and ozone depletion categories. These accumulations of impacts result from the "tree algorithms" used in the production of Ecoinvent databases. The inclusion of an Ecoinvent dataset in SimaPro will (by means of the tree algorithm) call up data from other databases on materials and processes it requires (*e.g.* the electricity required to make the material requested). In turn these will call up further datasets and so on (*e.g.* a portion of materials required in making the power plant that produced the electricity).

Although this method does not necessarily take data from outside the system boundary, it does require some caution when interpreting comparisons that are made against aggregated datasets (as provided for the benchmark product) which may not include as many "branches" or layers in their background data.

It is therefore necessary to examine the benchmark results carefully so as to be able to attach the greatest possible confidence to the comparisons made and conclusions drawn. What follows is a comparison of the benchmark product LCA results with datasets for similar products conducted by other LCA practitioners. This includes comparisons with Ecoinvent datasets.

4.2.2 Rockwool data set comparisons

As shown in the previous results section (Section 3.4.1) there appears to be a lack of ozone depletion and toxicity impacts in the Rockwool datasets when compared to the NFI materials, what follows is a comparison of the Rockwool data set produced by Schmidt *et al* (2003) and the results of various other inventories available regarding stone wool products.

4.2.3 Ecoinvent data set

The following comparison is made with the data supplied direct from Rockwool, compared to an existing Ecoinvent data set for a “rock wool” product and is displayed in Figure 21 on a functional unit basis.

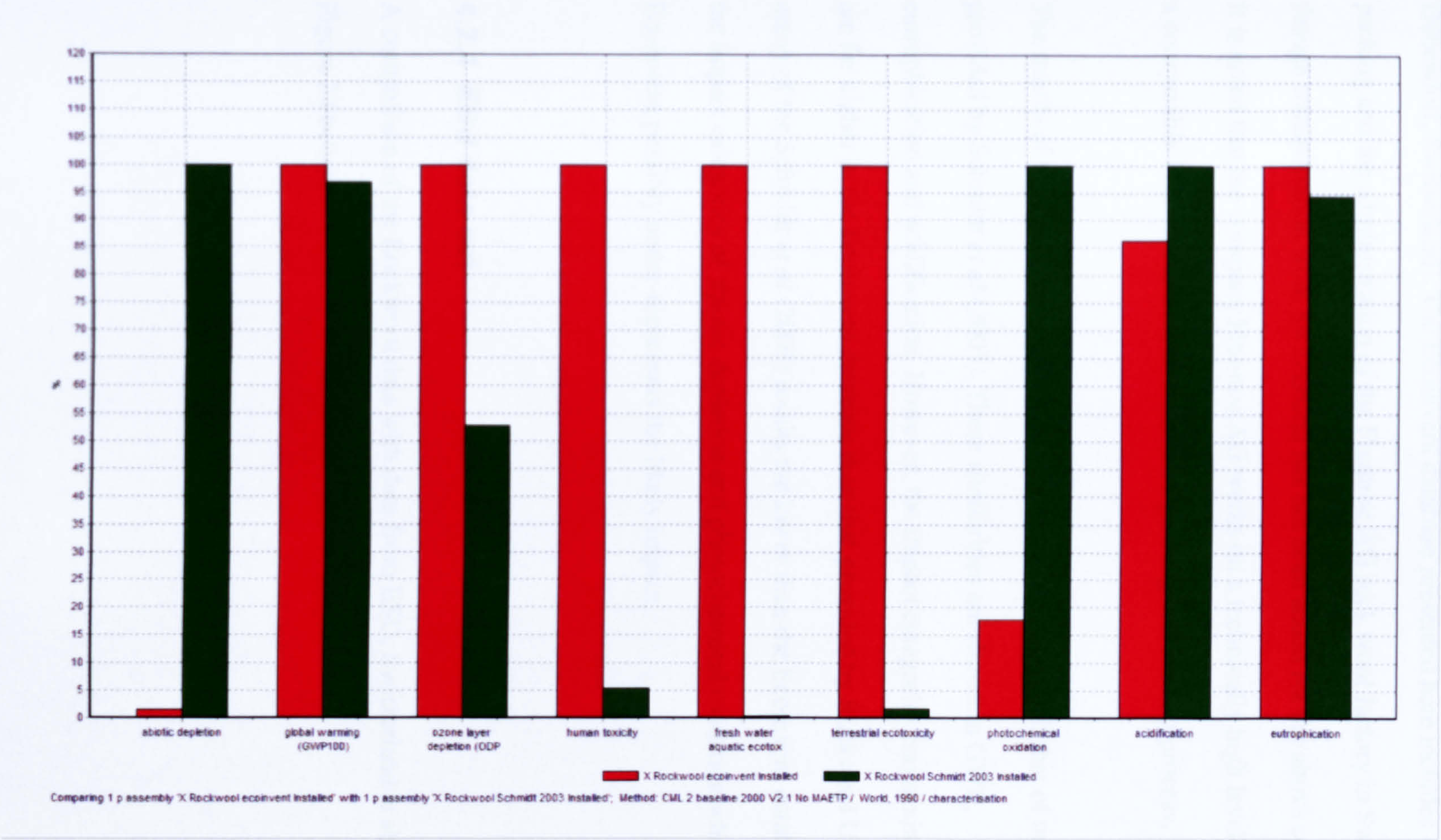


Figure 21 Comparison of Schmidt et al (2003) data with an Ecoinvent data set based on a Flumroc AG rock wool production plant in Switzerland

A comparison with an Ecoinvent inventory indicated that the benchmark data used for this study exhibited far lower or absent values in some environmental impact categories. This Ecoinvent data set was produced by EMPA-DU (Centre for LCI, Dübendorf, Switserland). The Ecoinvent database presented here includes mechanical packing and the administration of the Flumroc AG rock wool factory in Switzerland though transportation from Switzerland has not been added for the above comparison. It is noted that the company Flumroc AG works on a technically high level producing a comparable 112500 t/a, with an automated packing and loading process.

The results of the Ecoinvent database have some similarities with that of the data provided by Schmidt *et al* (2003). These similarities are shown in GWP, eutrophication and acidification. However, the impact categories concerning toxicity are far higher in the Ecoinvent database than that provided by Rockwool UK. Though many of the Schmidt *et al* (2003) results are lower than the Ecoinvent database, it is the impact categories of abiotic depletion and photochemical oxidation where Ecoinvent possibly under-represents the likely impact.

4.2.4 ESU data set

A comparison of the Rockwool data with data from ESU, Switzerland is shown in Figure 22 below.

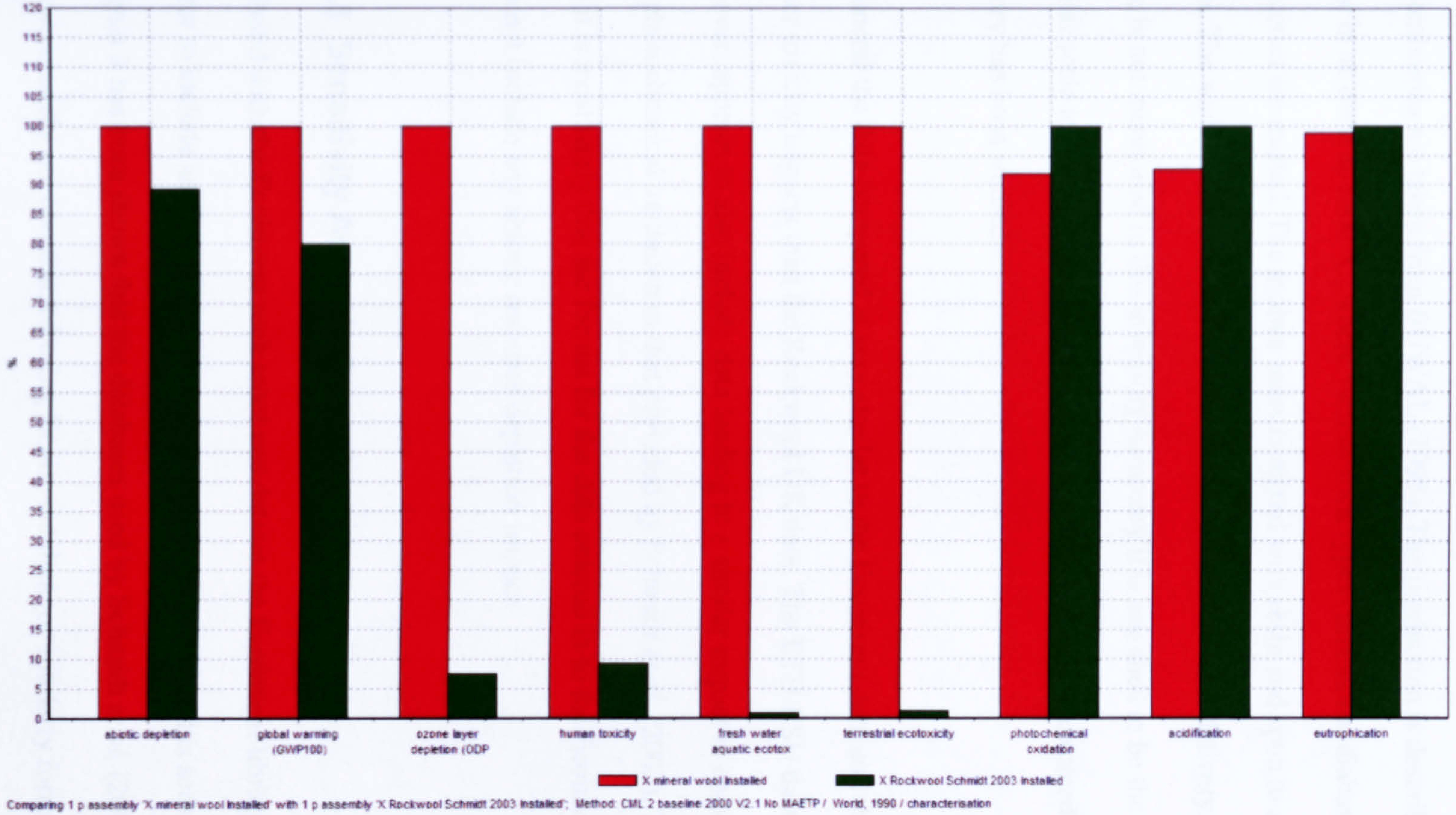


Figure 22 Comparison of supplied Schmidt et al (2003) data with data from ESU, Switzerland.

The Mineral wool ESU database is a total aggregated system inventory. The data is based on the Swiss production of a Flumroc rock wool product. It is not known if this is based on the same Flumroc product as described in the Ecoinvent data. The energy and emissions are taken from BUWAL (1995). The production is described as taking place in an oven at 1600 °C, where various rock types (limestone, diabase), cokes and briquettes are melted. The molten mass is mixed with resin and spun to a mineral wool. The wool is cured in an oven and further treated for final delivery. Though the scale is not mentioned in this inventory summary it is assumed to be the same or on a similar scale to that described in the Ecoinvent database as it is assumed the same factory has been studied.

In general the data compared is very similar to the Ecoinvent data and shows far higher toxicity impacts than the Rockwool UK data. The ETH-ESU database however, appears to also include data leading to a similar impact in abiotic depletion and photochemical oxidation to that provided by Schmidt *et al.* (2003). This being the case it is most likely that the format for the data entered in to the Ecoinvent library does not include any abiotic resource depletion impact.

4.2.5 Sensitivity Analysis Remarks

As found with the Ecoinvent rock wool and dataset the Ecoinvent library does not appear to include any abiotic resource depletion impacts. From this sensitivity analysis it has been shown that the databases used by Schmidt *et al.* (2003) were almost certainly not constructed using Ecoinvent data (or similarly formatted datasets), as such, ***caution is needed in comparisons with the NFIs in the abiotic depletion impact category.***

In general the impacts reported by Schmidt *et al* (2003) in the toxicity and ozone depletion catagories appear to very low. It is however impossible to say if this is a result of different processing or lack of reported data and thus, ***comparisons of toxicity and ozone depletion impact categories must also be made with this potential inconsistency in mind.***

Overall the stone wool datasets presented in this section appear similar in GWP which would suggest comparable amounts of "embodied energy" reported by all the examined stone wool datasets. It is however noted that the different fuel mixes used by the different countries electricity generation studied may have an effect on this data.

4.3 Marginal Analysis

In this study the term marginal analysis has been used to describe the technique of quantifying the impacts made by each of the contributing sub-processes and materials used in the final products that have been studied. This technique was used throughout the production of the NFI product LCAs to check for wrongly inputted data or inappropriate use of secondary data. By doing this there was a constant method of feed back when building the final LCA datasets.

Marginal analysis has been used here to identify the principal causes of impact for a product by each impact category. Both the negative and positive contributions to each impact category are assessed by the contributing process or material. Due to the quantity of potential end of life scenarios and for reasons of simplicity, the results displayed here are only for the ***cradle to installation*** portion of the LCA.

Due to the aggregated nature of the data set provided for the benchmark products, it is not possible to perform this type of analysis on the Rockwool product.

4.3.1 Thermafleece

Presented below are graphical representations of the contributing processes and materials in each of the CML impact categories for a ***cradle to installation*** analysis of the Thermafleece product. They are displayed as a percentage of the total impact for the product in Figure 23, and as a normalised representation in Figure 24.

From Figure 23 and Figure 24 the following observations have been made:

- In terms of abiotic depletion a large portion of the product impact is derived from the use of natural gas (methane) as a fuel, both in the final product production (used to melt the binder material) and as part of the scouring process within the production of clean wool.
- The use of diesel fuel in the transport of raw materials and finished product also gives an impact in most categories.
- A large negative contribution (*i.e.* environmental benefit) in terms of GWP is attributable to the renewable material fraction of the product, in this case wool.

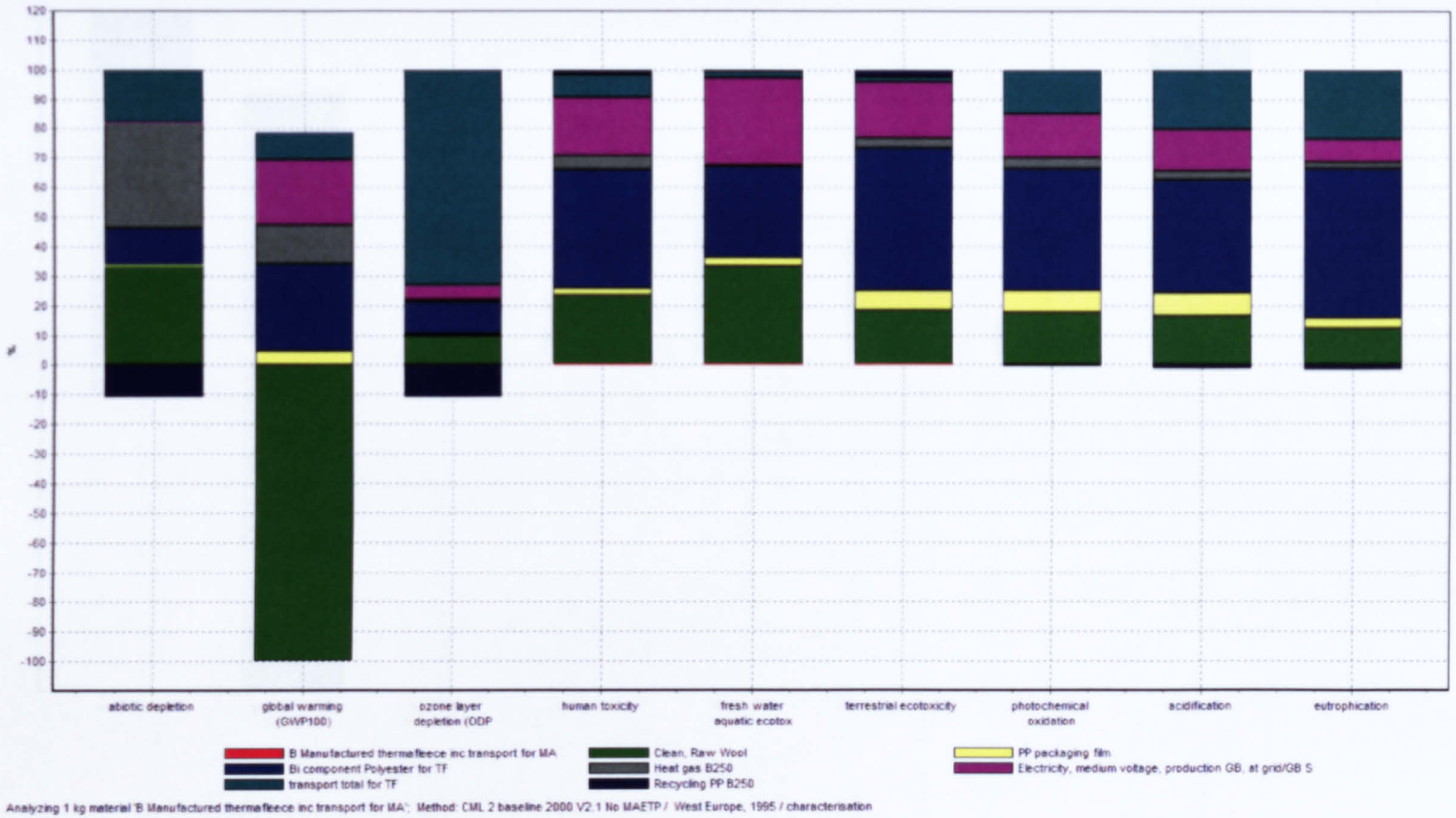


Figure 23 Marginal Analysis of the current Thermafleece product

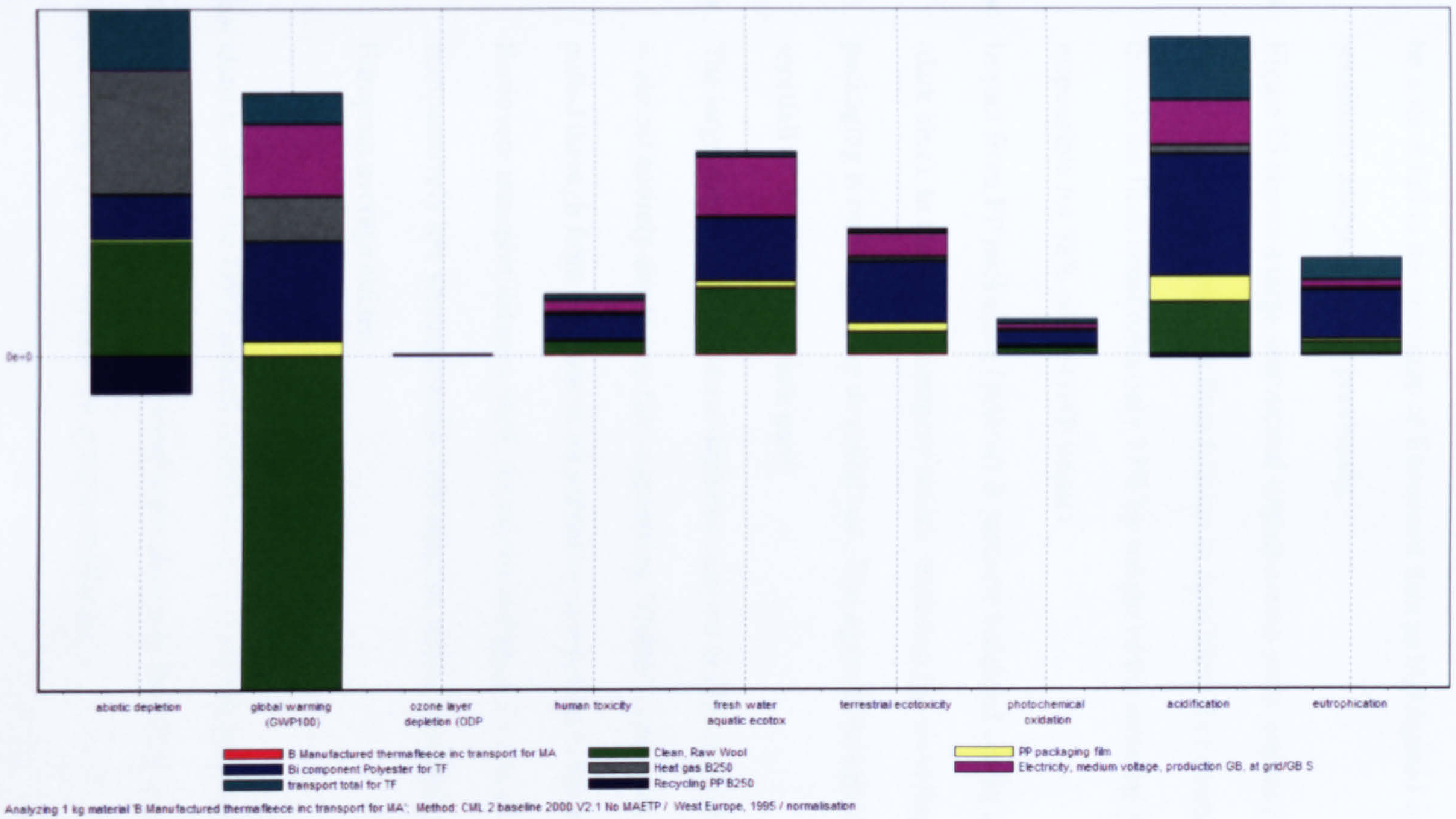


Figure 24 Marginal Analysis of Thermafleece normalised to the West European average citizen impact.

- The effect of the use of GB national grid electricity in the final production (pink) produces an impact in most catagories (presumed to be contributed to by the use of coal) though is not present in abiotic depletion. This is thought to be a short fall in the coverage of Ecoinvent data as highlighted in the sensitivity analysis section previously.
- Figure 23 shows a large detrimental impact across most impact categories by the bi-component polyester fibre (shown in light blue). For example even though the fibre constitutes only 15% by weight of the material input it is responsible for 38% of the GWP impact.
- Impact from PP packaging (yellow) is partially balanced out by its recycling (dark blue). In the impact category abiotic depletion the recycling of the packaging is outweighed by its initial use. This again is thought to be a shortfall of the Ecoinvent data used.
- The large contribution to ozone depletion (shown in Figure 23) from transport is almost entirely due to two fire suppressing "Halon" chemicals. This is pulled through from their use in oil refineries as reported in the rigorous Ecoinvent transport datasets used. As shown in Figure 24 it is of comparatively low environmental consequence when considering the West European average citizen.

A flow chart to show the GWP impact contribution by each sub-process or material is given in Figure 25 in order to give a visual appreciation of the relative contribution to this impact category of the various life cycle components.

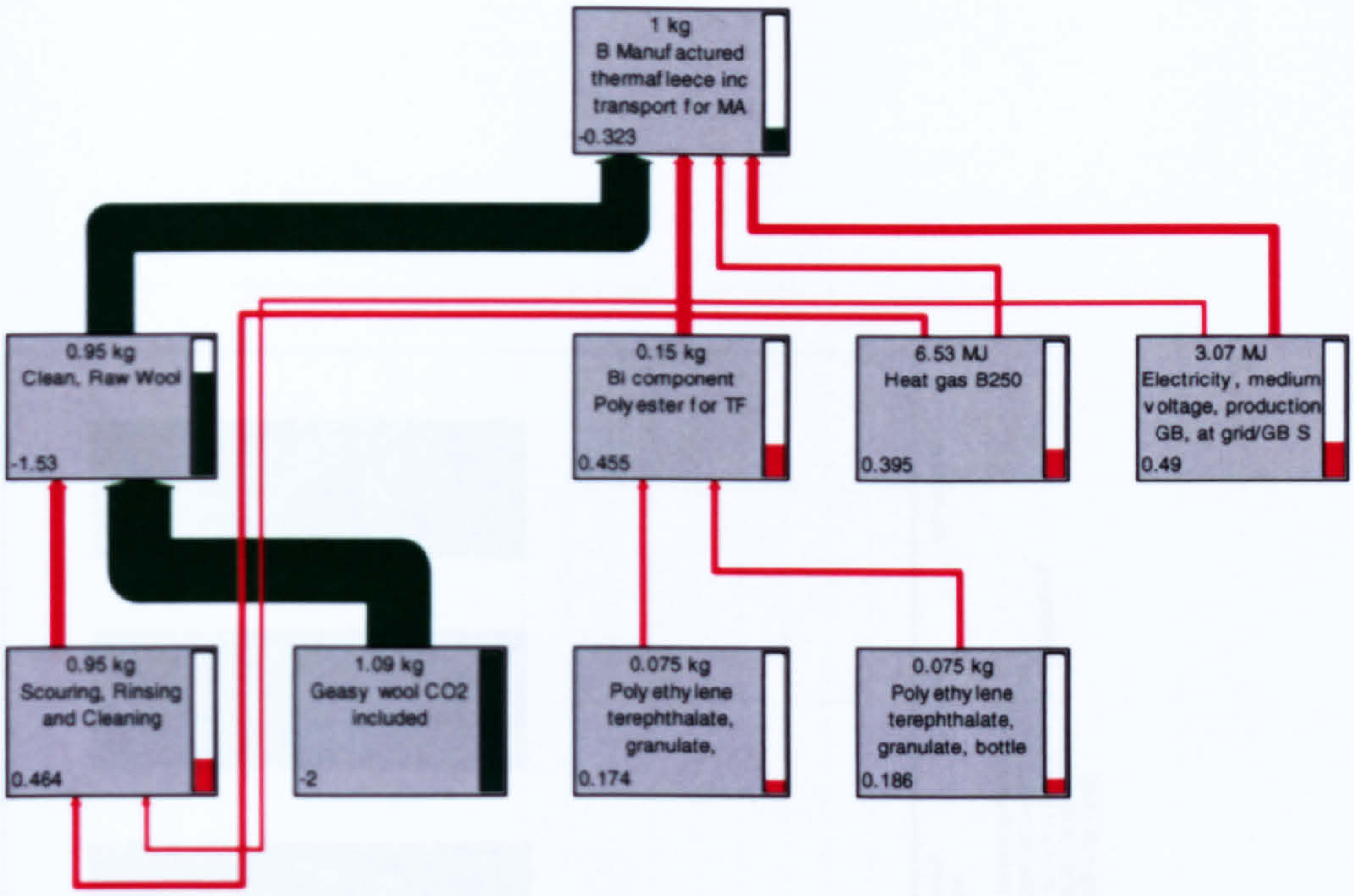
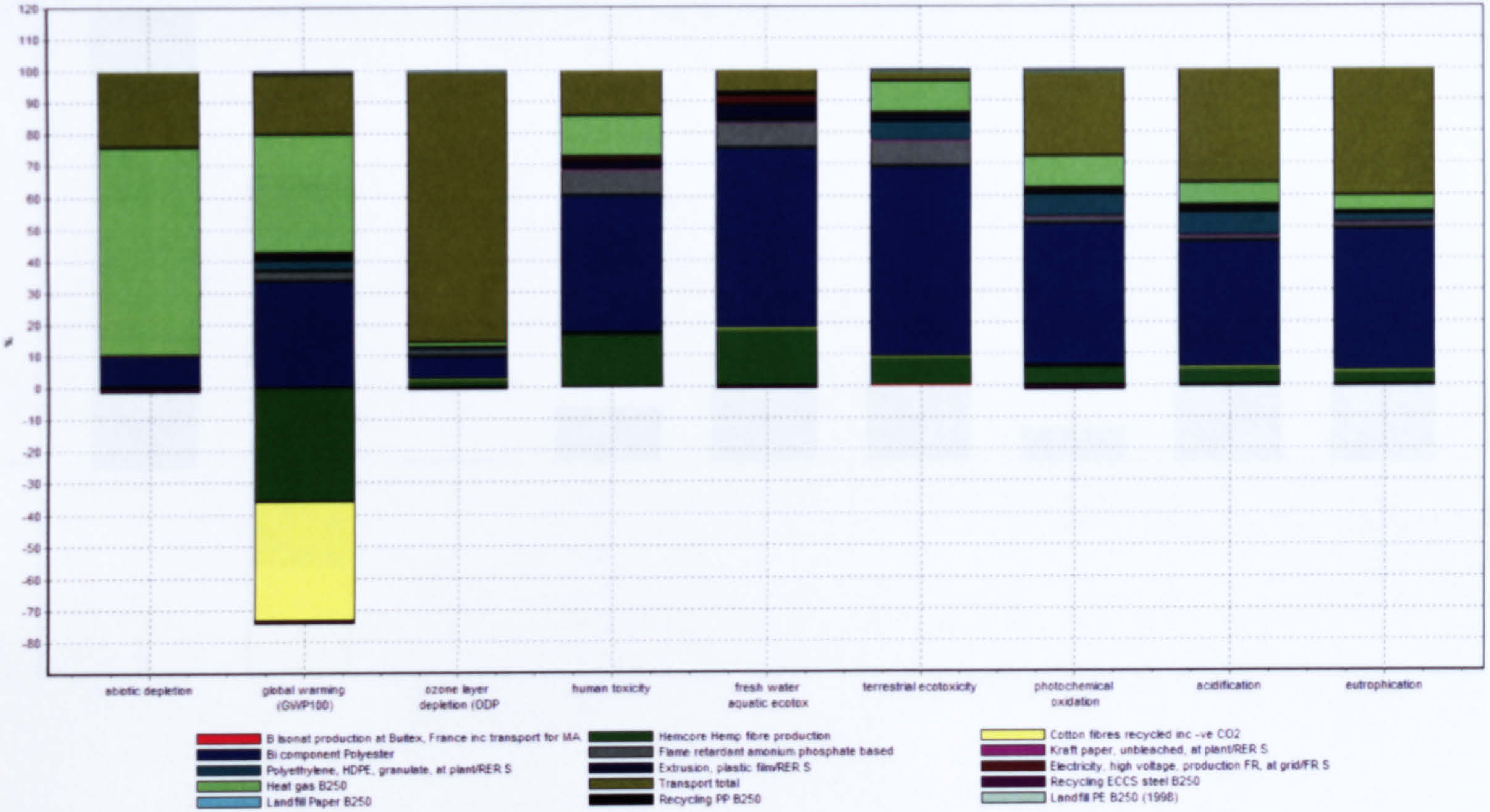


Figure 25 a flow chart to show the process and material contribution the overall product impact in terms of GWP. Impacts of less than 8% of the total have been omitted from the flow chart for clarity.

In Figure 25 the negative impact on GWP of the scouring process is apparent but is compensated by the positive effect of the wool (due to carbon sequestration) in the product "clean, raw wool".

4.3.2 Isonat

Presented in Figure 26 and Figure 27 are graphical representations of the contributing processes and materials in each of the CML impact categories for a ***cradle to installation*** analysis of the Isonat product. They are displayed as a percentage of the total impact for the product in Figure 26, and as a normalised representation in Figure 27.



Analyzing 1 kg material 'B Isonat production at Buitex, France inc transport for MA'; Method: CML 2 baseline 2000 V2.1 No MAETP / West Europe, 1995 / characterisation

Figure 26 Marginal Analysis of the current Isonat product

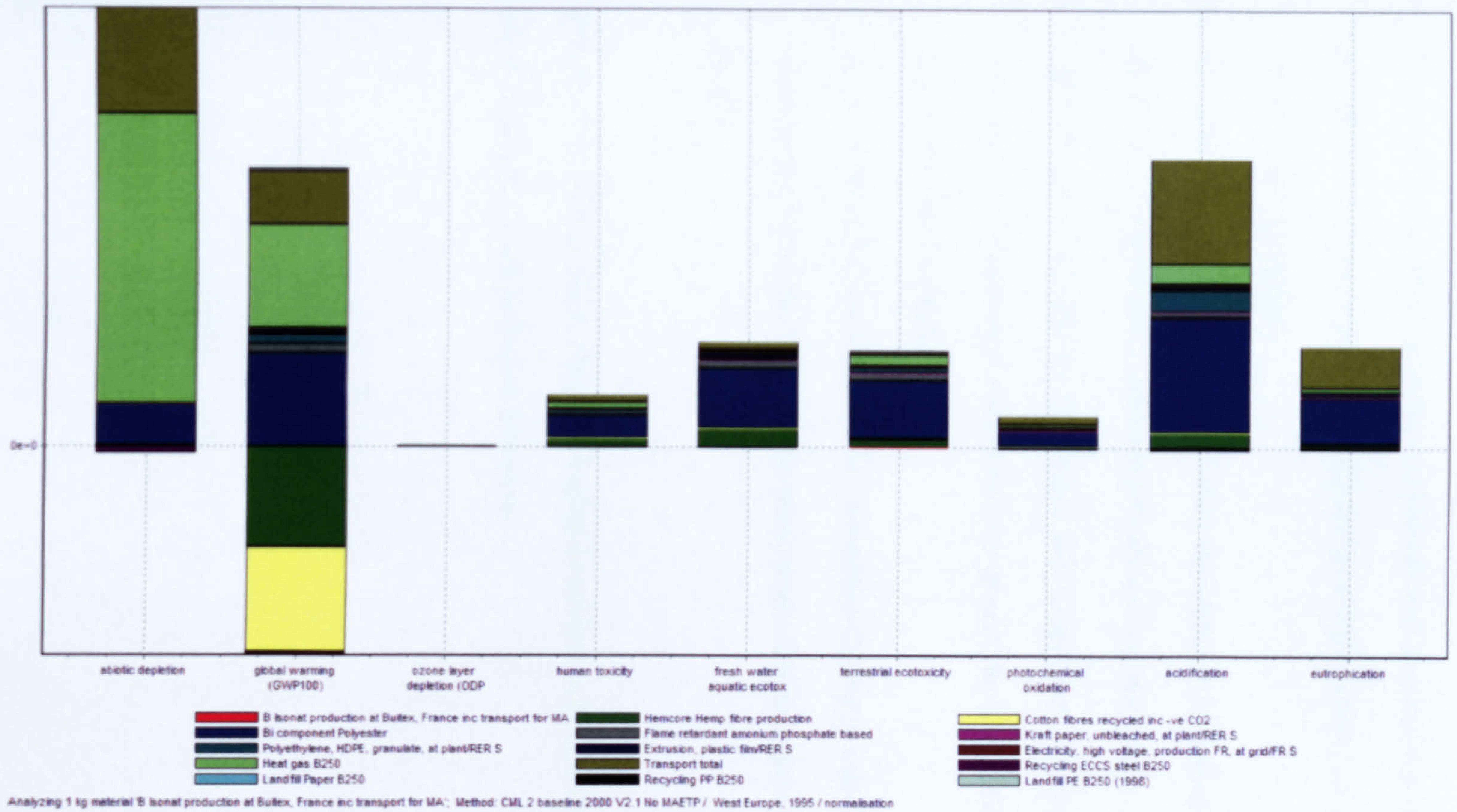


Figure 27 Marginal Analysis of Isonat normalised to the West European average citizen impact.

From Figure 26 and Figure 27 the following observations have been made:

- A large negative contribution (*i.e.* environmental benefit) in terms of GWP is provided by the renewable material fraction of the product, *i.e.* the hemp and recycled cotton fractions
- The relatively large quantity of gas used for drying and bonding the product (light green) contributes significantly to abiotic depletion and to GWP
- The bi-component polyester fibre (light blue) contributes a large detrimental impact across most impact categories even though the fibre constitutes only 15% of the material input
- The total transport (olive green) also contributes highly in many categories. A large proportion of this is due to the transportation of materials to and from France.

An example flow chart to show the GWP impact contribution by each major sub-process or material is given in Figure 28 below.

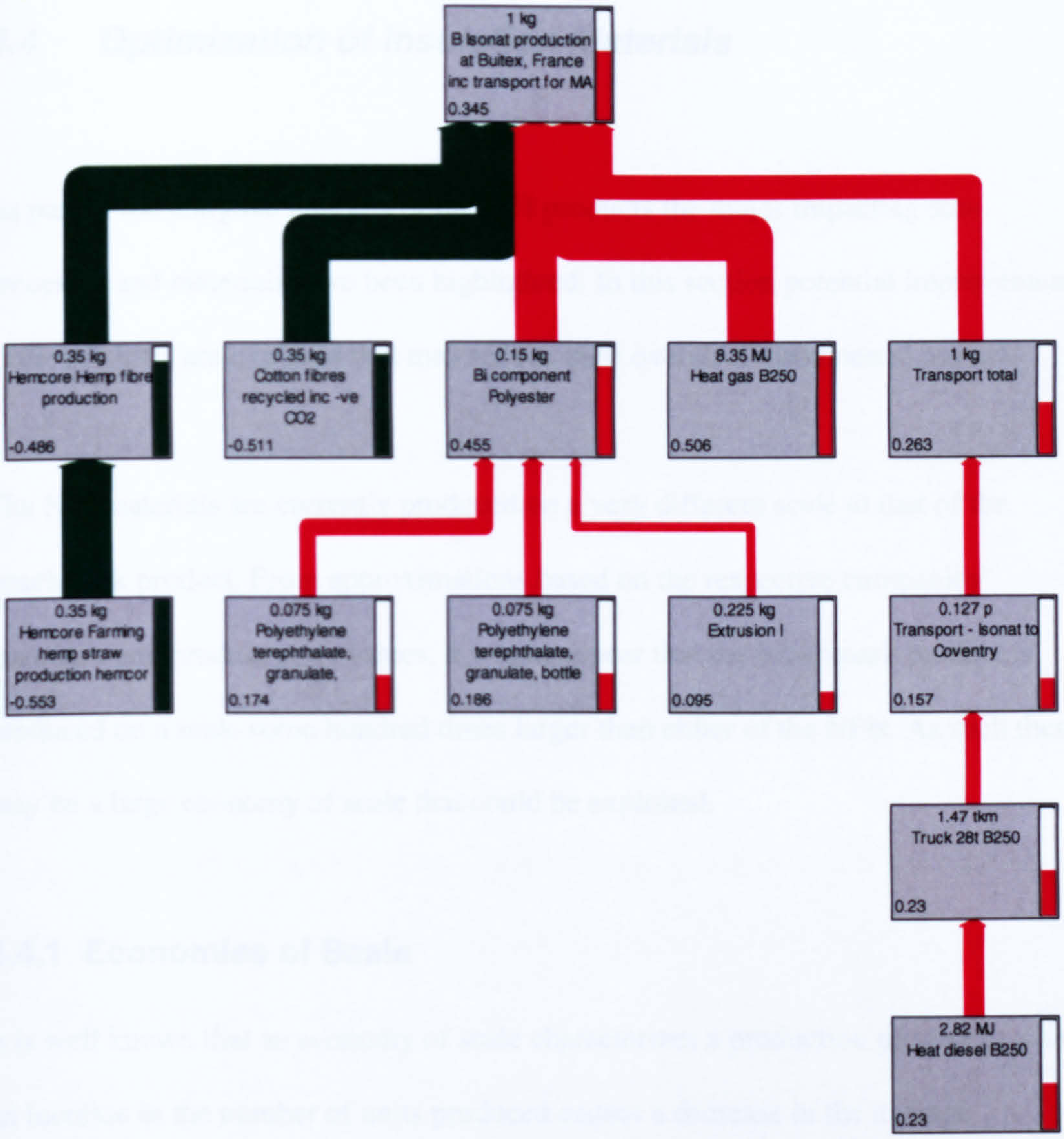


Figure 28 a flow chart to show the process and material contribution the overall product impact in terms of GWP. Impacts of less than 8% of the total have been omitted from the flow chart for clarity.

A notable observation from Figure 28 is that the impact of the specific transport function is visible and not cut off at the 8% contributing impact limit as shown. This particular transport function shown is that of the final delivery by truck of the Isonat material from the factory in France to the final installation in Coventry, with the majority of the impact stemming from the diesel used in the truck. The ferry journey taken as part of this function is not shown as it is of a low overall impact.

4.4 Optimization of Insulation Materials

As part of the marginal analysis of the NFI products the major impacting sub-processes and materials have been highlighted. In this section potential improvements to the products are explored that may reduce their overall environmental impact.

The NFI materials are currently produced on a very different scale to that of the benchmark product. From approximations based on the respective companies' turnovers and product sales values, it would appear that the benchmark product is produced on a scale some hundred times larger than either of the NFIs. As such there may be a large economy of scale that could be exploited.

4.4.1 Economies of Scale

It is well known that an economy of scale characterizes a production process in which an increase in the number of units produced causes a decrease in the average economic cost of each unit. This can also be true in terms of the energy used for each unit. Rockwool for example is a long established company and operates on very large scale in order to make their product as efficiently and cheaply as possible. This enables them to compete on price in the market place.

Taking the production of "glass products" in general as an example it is possible to see what effect scaling up production has on the energy usage for a furnace based production industry. This example is shown in Figure 29 below.

Figure 29 Graph to show the energy usage of different glass product manufacturers in approximate tons/hour against MJ/kg, between 0.25 and 80 tonnes/hour. Data supplied by Glass Technology Services LTD (Hartley, personal communication).

As can be seen from Figure 29 there is a marked decrease in energy requirements per tonne of product produced from 1 tonne/h to 15 tonnes/h production lines. However little or no decrease in energy appears to occur from 20 tonne/h to 80 tonnes/h. This "bottoming out" of the economy of scale shown by the glass product industry is thought to be similar to that of glass and mineral wool. The mineral wool benchmark product studied is produced at a large scale and is thus likely to have limited scope for significant further energy savings in manufacture. For example Rockwool has reduced its energy consumption per unit of output by 50% from 1975 to 2000 (DEFRA, 2006). Over the period of 1996 to 2003 the calculated embodied energy has only decreased from 18.2 MJ/kg to 17.3 MJ/kg (Rockwool, 2006a), *i.e.* 0.49%. An advanced status of manufacturing efficiency suggests that opportunities for further substantial efficiency gains and their associated environmental improvements may be limited.

4.5 *Optimization studies*

Due to the range and uncertainty over potential end of life scenarios and for reasons of simplicity, the results displayed here for improvement analysis of the NFIs are only for the ***cradle to installation*** portion of the LCA.

Every effort has been made to model optimization stages that could be commercially feasible for manufacturers of these materials. The intention is to gain an understanding of the scale of effect of such operations. It is not in any way implied that the optimization stages modelled will be adopted and the results of the analysis are, equally, ***not*** an estimation of the ***best possible*** products made from natural fibres.

4.6 *Optimization of a Sheep wool fibre based product*

Shown here is a selection of potential "optimization" methods for a sheep wool product. These include the replacement of the binder material, a reduction in the use of fire retardant and a reduction in density. There are other optimization stages that could be considered for a new product. However due to a lack of data and/or commercial sensitivity, they have not been considered here.

4.6.1 Replacement of binder material

It was identified in the marginal analysis that the polyester based bi-component fibre impacted in most categories relatively highly. The replacement of the current bi-component fibre used to bind the fibres is a very near future option for product improvement. A potential bio-derived replacement is that of poly-lactic acid (PLA) based fibres. Bi-component PLA fibres are available "off the peg" currently and show potential for environmental impact reduction. Modelled here is a direct replacement of the existing polyester fibre with the same quantity of PLA based fibre in the standard Thermafleece product. The PLA dataset used was produced at Imperial College London.

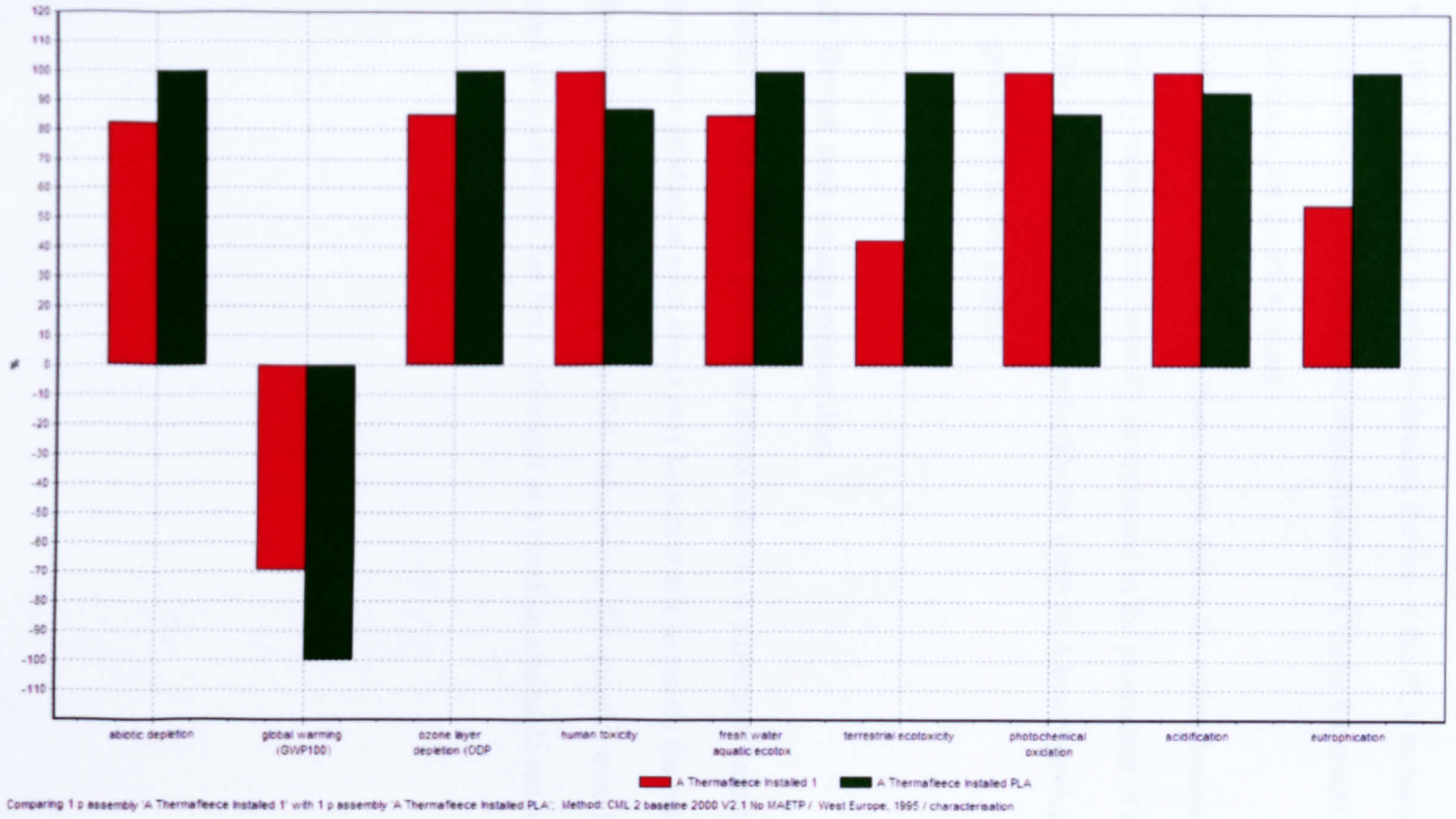


Figure 30 Graph to show the effect of producing the current material with a PLA based binder

Using a PLA binder would appear to improve the products impact in some categories while generating more impact in others. The following observations can be made:

- GWP in particular is reduced through the use of the PLA material. This is attributed to by the additional sequestration of CO_2 by the maize used as a feedstock for the PLA fibres.
- Other impact categories are made worse due to the maize feedstock and high energy requirements currently incorporated in the production of the material. The latter has potential for reduction for some PLA based products as production scales increase.

4.6.2 Borax salt usage reduction

A reduction in the current quantity of Borax solution is a potential improvement to the Thermafleece product as such levels may be acceptable to satisfy the relevant fire safety standards. Modelled here is a 30% reduction in the quantity used in the standard product as this has been estimated as a possible attainable reduction.

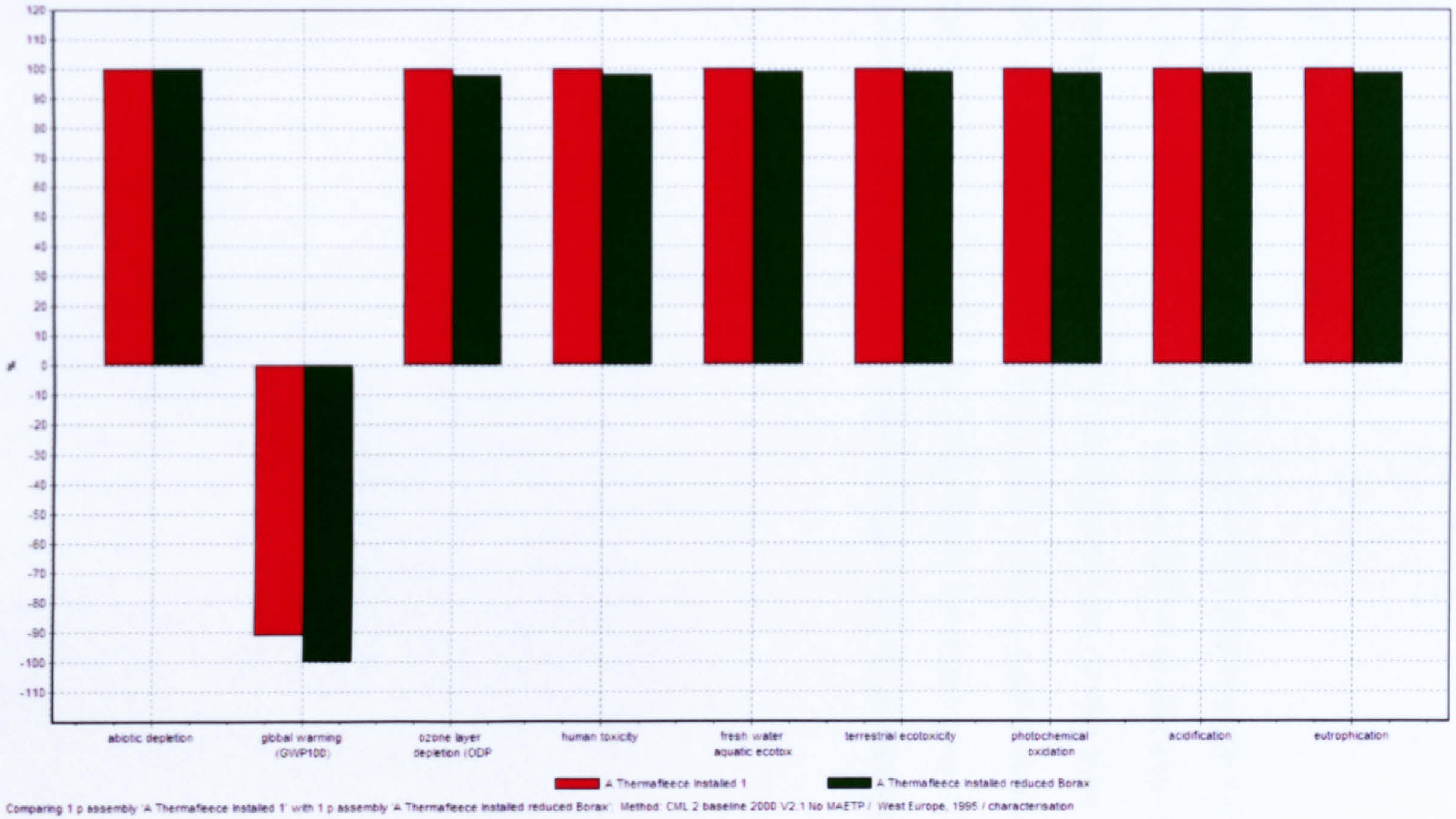
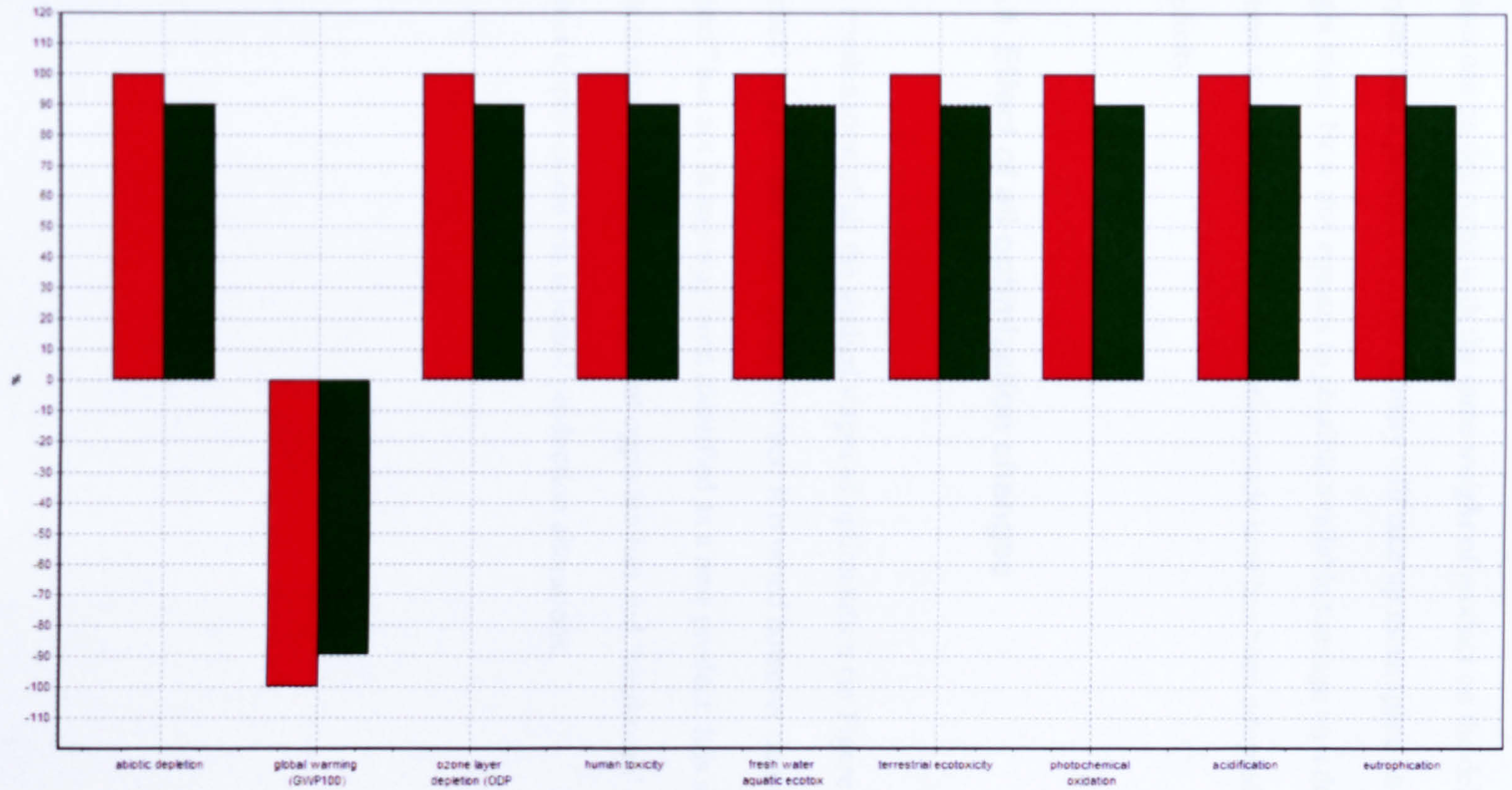


Figure 31 Graph to show the effect of a reduction in Borax usage in the current Thermafleece product

The reduction in Borax usage has a small but notable impact on most impact categories the highest impact reduction being in GWP due to a reduction in the burden carried through from the energy required to produce the borax salts.

4.6.3 Density Reduction

In previous discussion it has been shown that a lower density product will carry a lower environmental burden if it fulfils the same functional unit. It has been calculated by the producers of the Thermafleece product, Second Nature, that a reduction in density from 25 kg/m^3 to 22 kg/m^3 could be possible without any notable change in production requirements or performance. The implications of this (approximately 10%) reduction in functional unit weight are presented here in Figure 32.



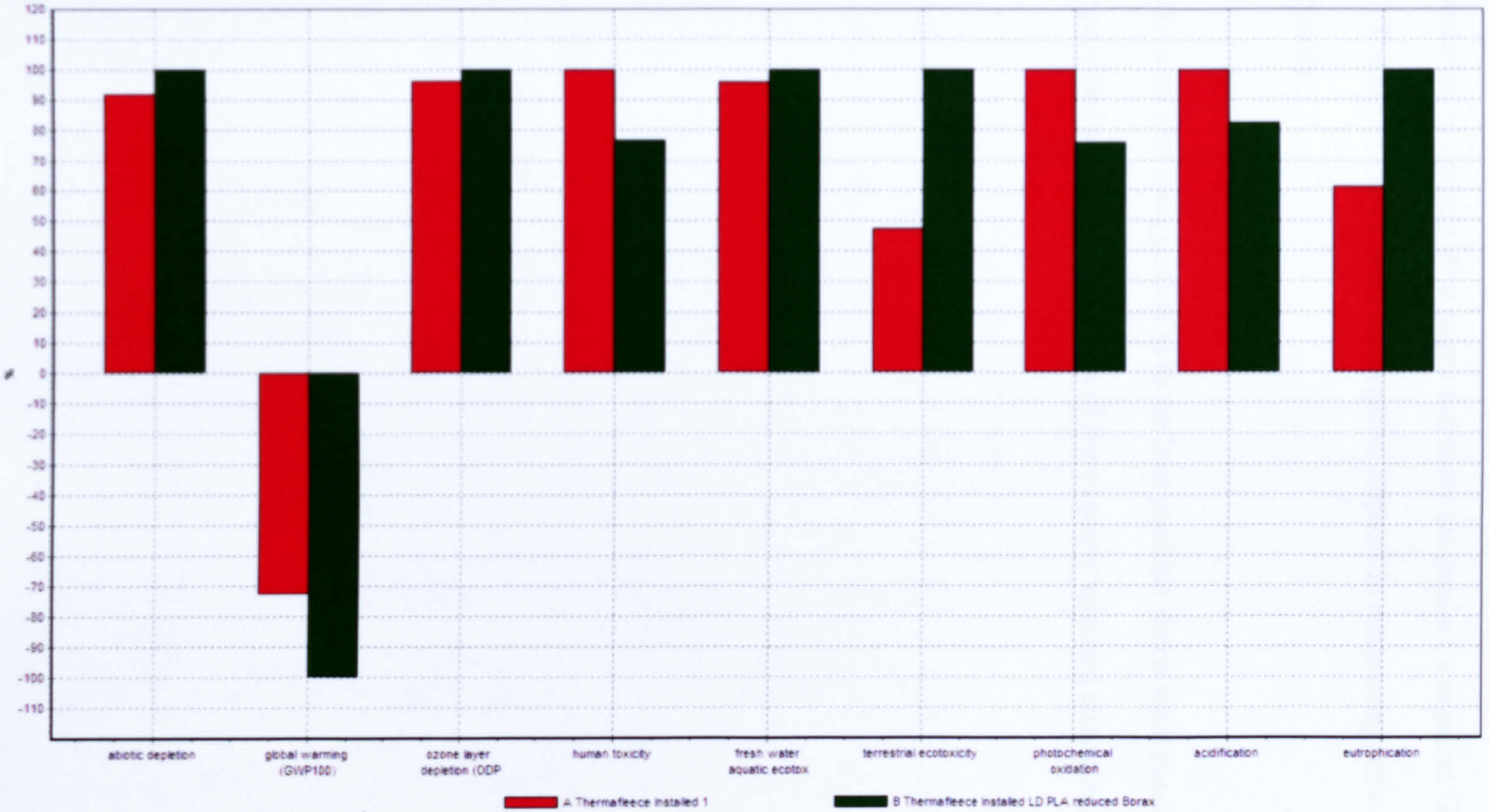
Comparing 1 p assembly 'A Thermafleece Installed 1' with 1 p assembly 'A Thermafleece Installed LD'; Method: CML 2 baseline 2000 V2.1 No MAETP / West Europe, 1995 / characterisation

Figure 32 Graph to show the effect of a reduction in density in the current Thermafleece product

As can be seen from Figure 32 the products environmental impact has been proportionately reduced across all categories, in reality there ***may*** be a small fluctuation caused by transport as it has been assumed here that the lower density product can be delivered with the same ***weight*** of product on the delivery truck. It is accepted that a product of lower density will take up more space on a weight for weight basis. How this equates to possible available tonnage on a delivery truck has not been studied and so the assumption made here has been adopted for reasons of simplicity.

4.6.4 Effect of all optimization changes

The combination of all the studied stages of optimization (in Figure 33) reveals the potential of a ***possible*** near future product. It is noted however that this "potential product" has not in any way been identified as a new product. It is merely an example given to show potential development opportunities and 'headroom' for continued product improvement via selected production alterations.



Comparing 1 p assembly 'A Thermafleece installed 1' with 1 p assembly 'B Thermafleece installed LD PLA reduced Borax'; Method: CML 2 baseline 2000 V2.1 No MAETP / West Europe, 1995 / characterisation

Figure 33 Graph to show the effect of a reduction in borax, a density reduction and switch to PLA binder on the Thermafleece product.

It can be seen from Figure 33 that a sheep-wool based product, if produced with all of the optimization stages discussed previously, shows both positive and negative environmental effects when compared with the Thermafleece product. The combination of optimization stages increases the product's negative GWP by over 25%. The use of PLA causes the negative impacts in some categories as discussed previously.

This is in no way a suggestion as to the best possible sheep wool based product and is only provided to display the effects of the example minimal alterations.

4.7 Optimization of Hemp fibre based product

There is great scope to reduce the environmental impact of the current Isonat product. A wide selection of potential improvements that have been identified from the marginal analysis is studied here with a discussion on the potential demand for land for hemp cultivation for NFI production.

4.7.1 UK Production

UK Production of an Isonat or a similar Hemp based product is seen as a likely scenario given the current increase in demand from the UK market. As well as improved supply logistics which may result in a more reliable product for the UK market, the obvious reduction in transportation is of real benefit to the products' environmental profile as shown in Figure 34. Studied here is the effect of transport reduction resulting from assumed production in the UK on the basis that such production is located close (~10km) to the current hemp primary production facility. Also studied here is the effect of removing the recycled cotton fraction as this is likely to be replaced by hemp fibre if such a site change were to happen. The cotton fraction is currently used due to the close proximity of the French production site to large quantities of usable recycled cotton.

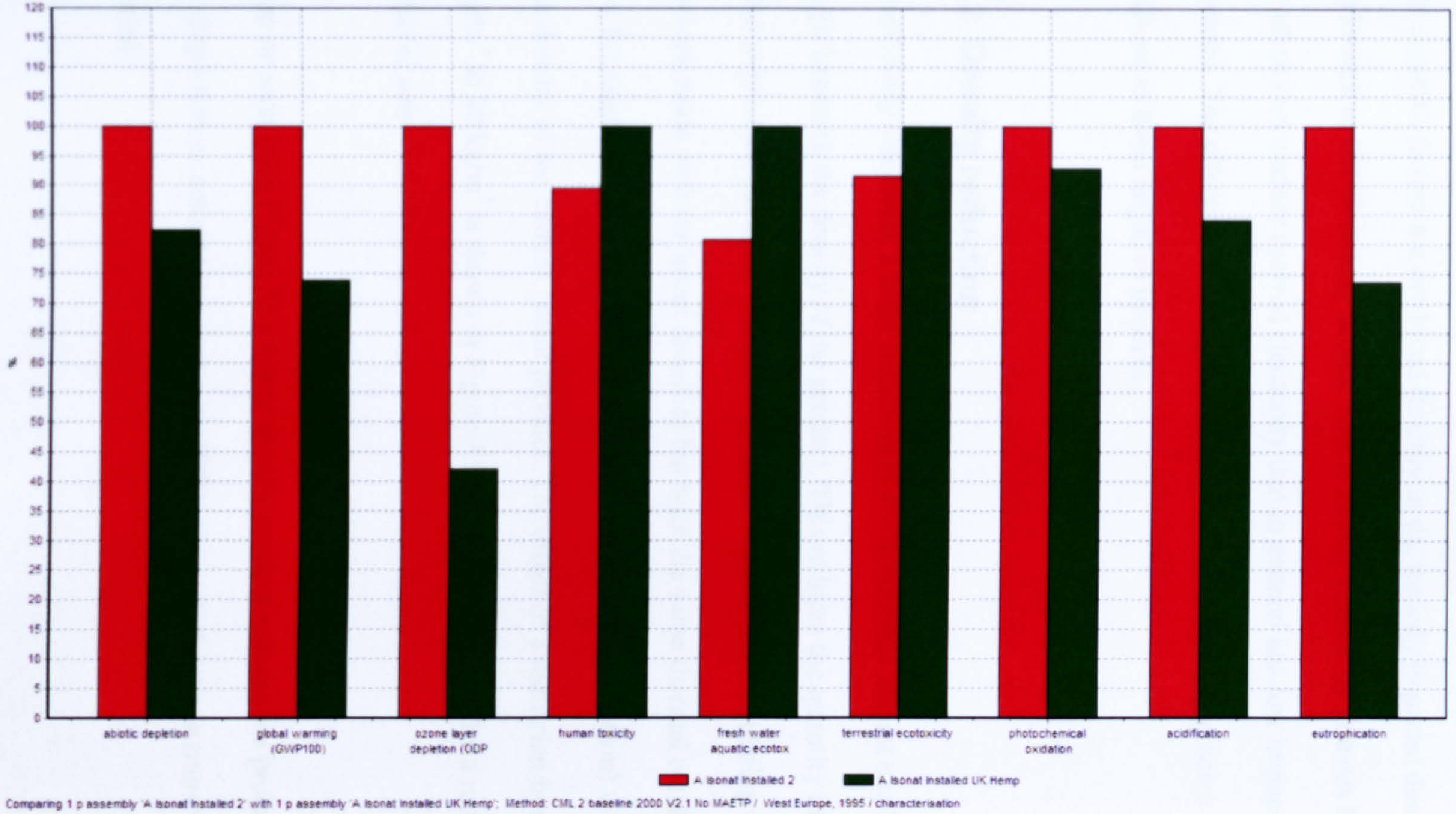


Figure 34 Graph to show Current Isonat production by Buitex in France compared to UK production with the recycled cotton fraction replaced by an increase in hemp fibre usage.

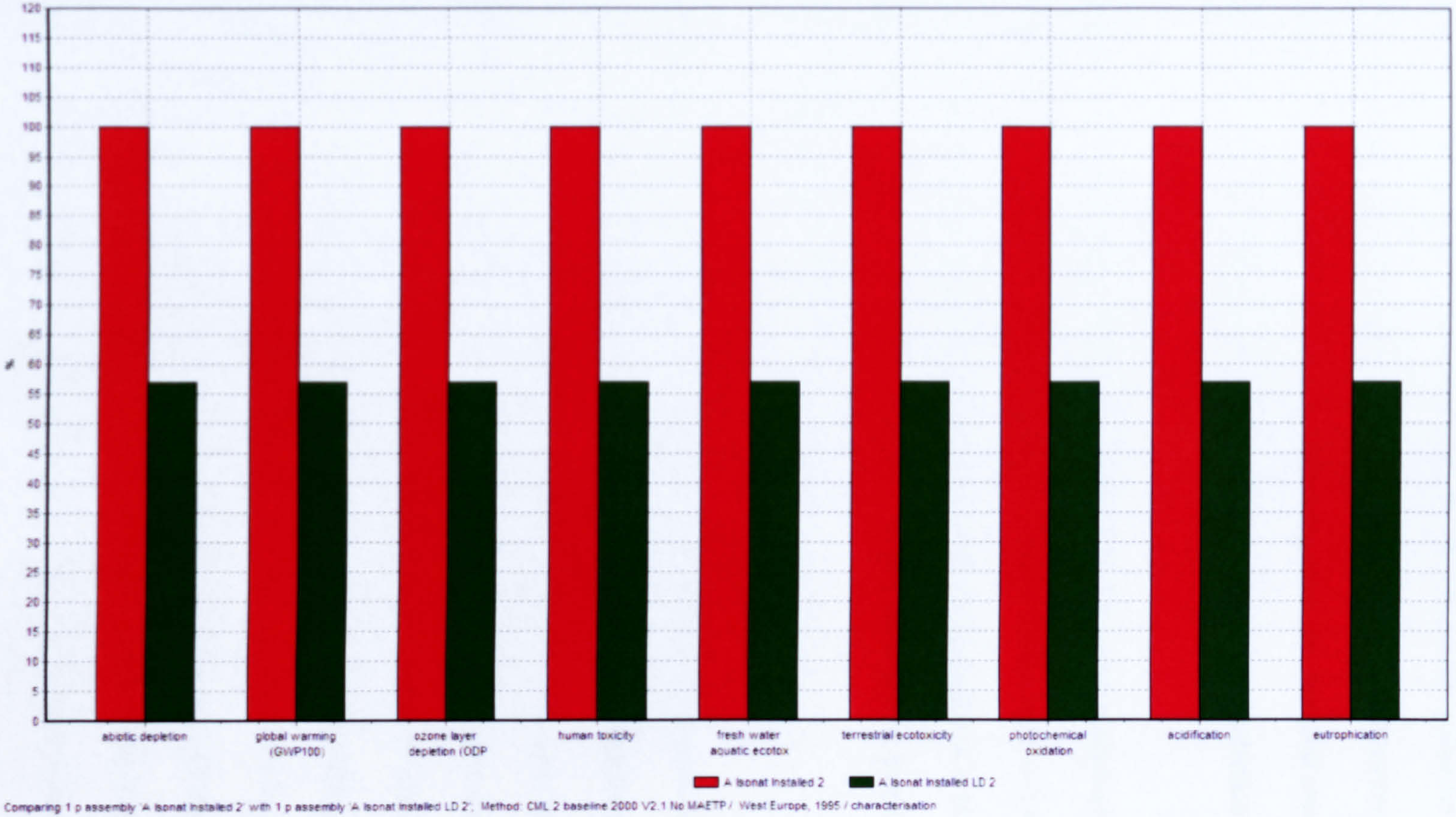
An insulation production facility in the UK would substantially reduce the amount of transport required for the UK market, which has a large beneficial effect on the installed material's GWP and also to ozone layer depletion potential.

Some negative factors are produced (mainly in the toxicity impacts) due to the switch from French to GB electricity mixes. This is mainly caused by Frances high dependency on nuclear derived electricity that in general has low impacts in these categories. The effective doubling of the scale of hemp farming process will also contribute to these negative impacts.

4.7.2 Density reduction

As previously discussed, a large reduction in environmental impact can be gained through lowering the density of the product. This reduces the quantity of material needed to produce the same volume of product. Natural fibre insulation materials have been made with far lower densities but with the same thermal conductivity value, for example a previously available flax based product (Natilin) was under 60% of the density of the current Isonat product. The effect of a reduction in density from 35 kg/m^3 to 20 kg/m^3 is shown in Figure 35 below as calculated by a reduction in functional unit.

As can be seen from Figure 35 a lower density product reduces the product's impact by a proportionate amount (*i.e.* just over 40%) when no change in transport impact is assumed.



Comparing 1 p assembly 'A Isonat Installed 2' with 1 p assembly 'A Isonat Installed LD 2'; Method: CML 2 baseline 2000 V2.1 No MAETP / West Europe, 1995 / characterisation

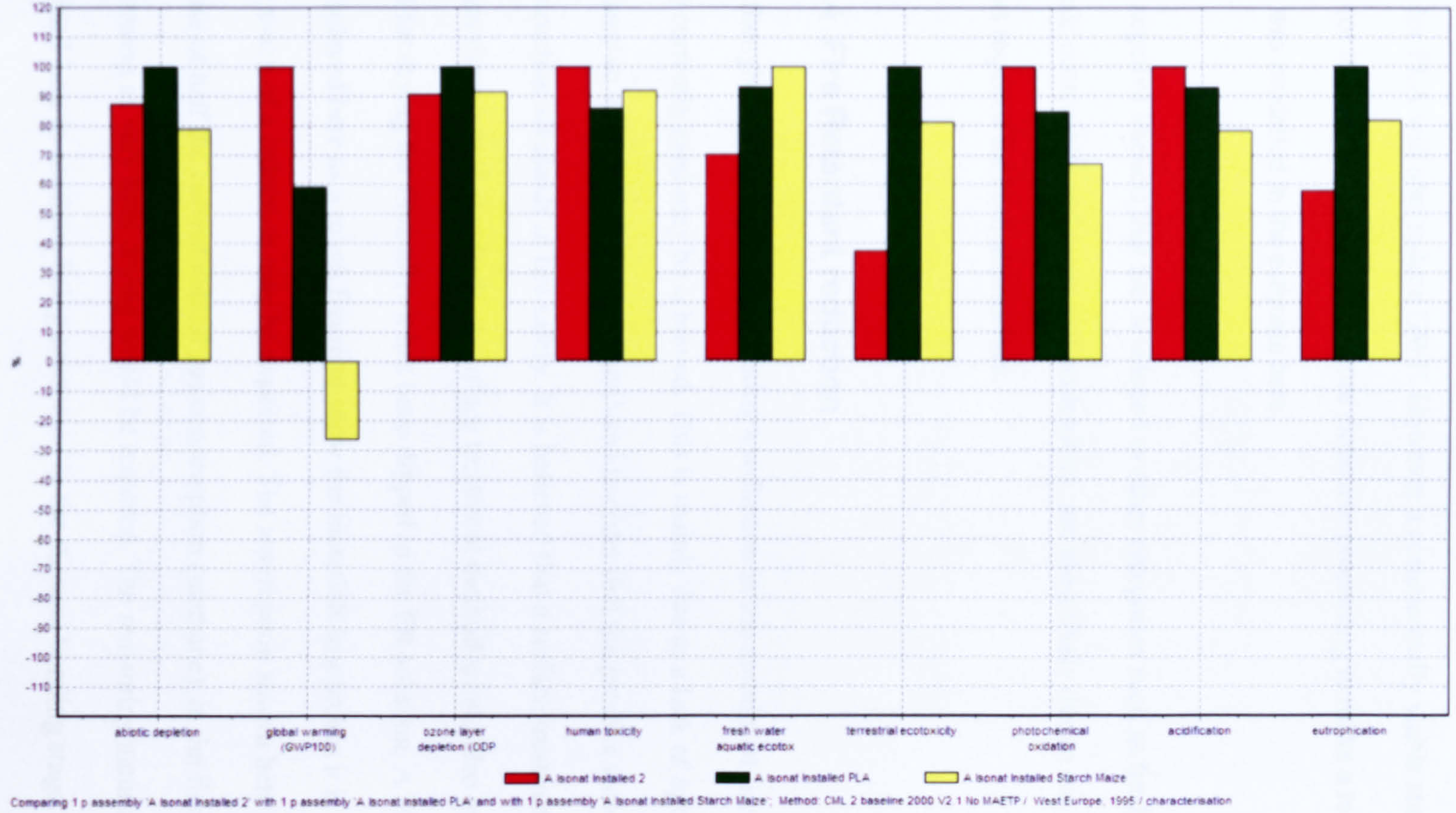
Figure 35 Graph to compare the current Isonat production buy Buitex compared to a reduced density (20 kg/m3) material.

4.7.3 Binder Material Replacement

The marginal analysis identifies that material replacement provides scope for environmental impact reduction, especially in the area of energy use. This large energy saving comes mainly from replacing the bi-component polyester binder as it is a very energy intensive material to produce and based on a fossil reserve. Omitting the purchase of a material from Korea, where the polyester material used in the Isonat product is made, would further reduce the energy used in transportation.

FIT (Fiber Innovation Technology) in America, produce a bi-component fibre which has been trialled by Buitex with only minor technical issues, such as a requirement for a tighter temperature range in the curing process. It is the higher cost however that currently prevents its usage, as it has been identified as an almost direct replacement for the polyester based binder.

Starch based binders have been tried by other natural fibre insulation manufacturers. In a German hemp product (no longer in production) the starch binder used was found to be too brittle after long periods to be a reliable material (Newman, personal communication). It is still however possible that other more reliable starch based thermo plastics that are currently being developed may provide an alternative binder and so an estimate of their impact has been studied here and their effect is shown in Figure 36. The PLA binder was modelled using a data set produced by Imperial College, London and the starch binder was modelled by using existing Ecoinvent starch and extrusion datasets. Both were modelled as a direct replacement for the current polyester fibres with appropriate adjustments made to the transport to include shipping from America.



Comparing 1 p assembly 'A Isonat Installed 2' with 1 p assembly 'A Isonat Installed PLA' and with 1 p assembly 'A Isonat Installed Starch Maize'; Method: CML 2 baseline 2000 V2.1 No MAETP / West Europe, 1995 / characterisation

Figure 36 Graph to show the effect of replacing the current binder with a PLA or Starch based material

As shown in Figure 36 both the starch and a PLA based binder were found to give a large reduction in GWP over the Isonat product. This is due to the alternative binder materials sequestrating CO_2. In the case of the starch binder the lower energy inputs than for PLA will also reduce GWP. However a commercially viable starch binder may (or indeed may not) require more extensive processing to make a reliable product than was modelled in the estimate here.

The negative impacts that are developed in other categories such as fresh water aquatic ecotoxicity and terrestrial ecotoxicity, are most likely due to the farming inputs required for both alternatives.

4.7.4 Fire Retardant reduction

It is thought that through further testing a reduction in the amount of fire retardant (FR) currently used may be achieved. This is mainly due to a lack of optimization in this area so an over estimate has been used in order that the product would not fail the construction standards in fire safety. It is believed that a surface treatment is sufficient to pass the required standards. A surface treatment method would also mitigate the need for drying the fibre after it has been dipped in the FR solution. A 30% reduction is displayed here as a rough figure to show the materials impact but it is uncertain how much of a reduction may be expected. The assumption shown here also includes the use of half the current natural gas consumption (methane), in the final product processing as very little drying would be required. The remaining natural gas used is assumed here to continue being consumed in the thermal bonding stage.

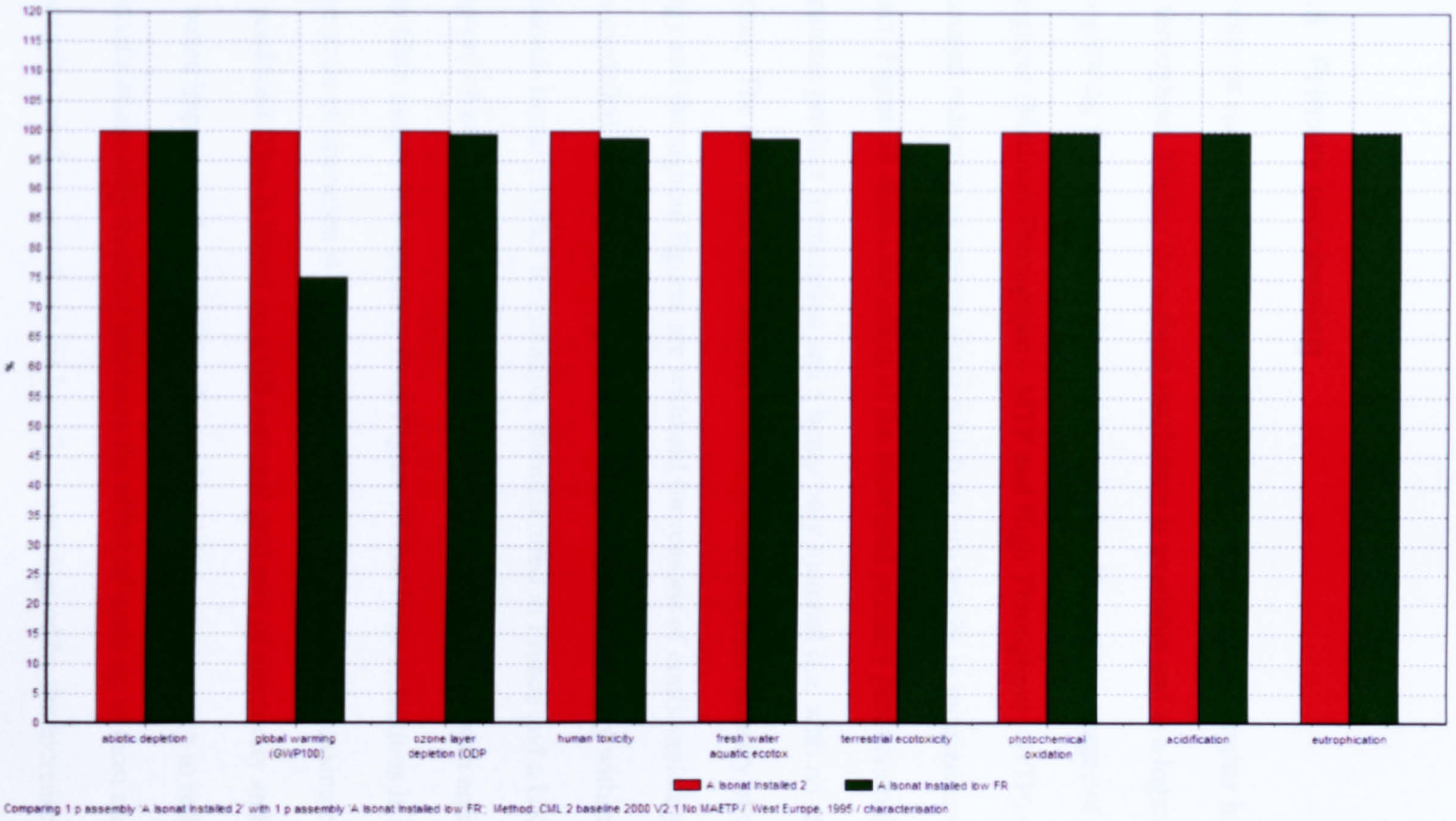
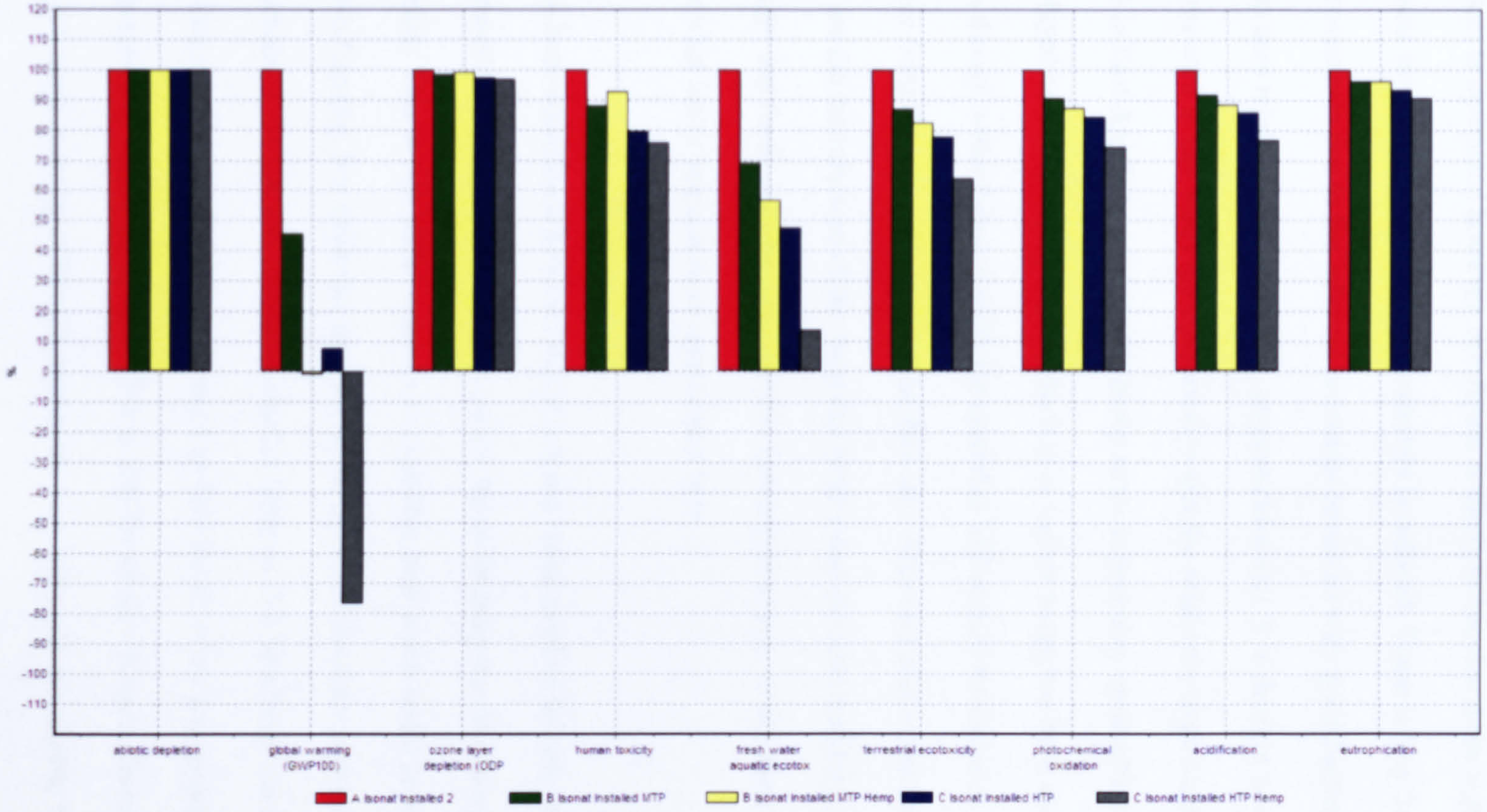


Figure 37 Graph to show the effect of reduced fire retardant usage *i.e.* 33% reduction in FR and reduced energy use from lack of drying requirements

The reduction in GWP shown in Figure 37 of some 25% accrues from reducing the FR quantity due to: 1) the high consumption of energy in the production of the ammonia (poly) sulphate material and 2) reduced energy usage from the reduced gas usage in drying also results in a reduced GWP.

4.7.5 Primary processing

The current energy usage for the primary processing of hemp is rather high due to the low throughput. Higher throughput machinery is available and is a logical next step for a growing fibre processor. Studied here is the effect of two stages of increased throughput (Medium Throughput – MTP and High Throughput – HTP) with their associated reduction in energy usage which in turn results in reduced environmental impact. Figure 38 shows the effect of the increased primary production throughput on the current product formulation and a hemp only material (*i.e.* with no recycled cotton fraction). The data used was derived from consultation with industry, though the exact energy and throughput figures are withheld for reasons of confidentiality. They have been modelled by reducing the primary energy usage accordingly within the traditional Isonat product formulation, manufactured in France and a UK poduced hemp-only based product (*i.e.* with the cotton fraction replaced with an increase in hemp fibre usage). It is apparent from Figure 38 that large reductions in GWP occur as the scale of operation is increased due to the reduction in processing energy per unit produced. This is based on a GB national grid mix of electricity and so the fossil fuel based impacts such as acidification and toxicity, are also seen to reduce. The effect of a hemp only material increases the effect of scale up in most cases, except for toxicity based scores where the benefit is outweighed by the increased hemp farming input.



Comparing product stages; Method: CML 2 baseline 2000 V2.1 No MAETP / West Europe, 1995 / characterisation

Figure 38 Graph to show the effect of a 2 stage increase in primary production throughput (Medium Throughput – MTP and High Throughput – HTP) on the current French produced Isonat product formulation and a UK hemp only material

4.7.6 Farming

From the marginal analysis of the Isonat product it can be seen that farming only contributes to a small fraction of the total impact of the product. As a potential product is optimized however, this figure is likely to become more significant as the impacts from other processes and materials is reduced. There is less "headroom" for improvements due to the inherent processes involved with good farming practice (*e.g.* hemp uses relatively little fertiliser, no pesticides etc). It is thought however that the figures used in this study are conservative and the relatively large scale farming that is used in East Anglia to produce the hemp straw is probably more efficient than is displayed here. For example, no reduction in tractor usage has been accounted for even though wider farming tools are used that will reduce the distance travelled by the tractor from the examples used in the data sets. Also included in the Ecoinvent data sets are the manufacture of the farm machinery and the farm buildings. As such it is thought that further studies into specific farming practices would most likely show somewhat lower impacts than represented here.

It has been considered however that if a hemp based product became popular through increased market demands, the demand on hemp farming would consequently increase. This in turn raises a question regarding how much could be supplied by British farming. For example, in order for hemp based insulation products to supply the whole of the UK loft insulation market (approx. 6.2 Mm^3/year), it is calculated that this would require the equivalent of an 80 tonne/h straw processing line fed by approximately 12,000 ha of land. This is 0.064% of all UK agricultural land. Though this is a large quantity of land, it represents very little use of valuable food production land.

The quantity of fibre produced would also provide some 40,000 tons of shive annually which, with efficient and economically competitive production, could provide a notable supply of biomass for local heating and energy plants in line with Government targets for renewable energy, or could be utilized in hemp-lime construction techniques which are increasingly popular. This land use figure also assumes that the insulation product would be produced at the same relatively high density that is supplied currently. The production of a lower density product would require a proportionately reduced amount of crop and land area.

4.7.7 Combination of most likely optimization

A combination of the optimizations described above has been selected to represent the near future potential of a logically optimised product. The optimizations combined are:

- Reduction in product density from 35 kg/m^3 to 20 km/m^3
- Production in the UK
- A hemp only based by omitting the recycled cotton fibre portion
- Reduced fire retardant usage with consequently reduced drying requirements
- A switch to a PLA based bi-component binder.
- An increased throughput in primary processing

The effect of a combination of the optimizations described above shows a very strong environmental profile as shown in Figure 39 below

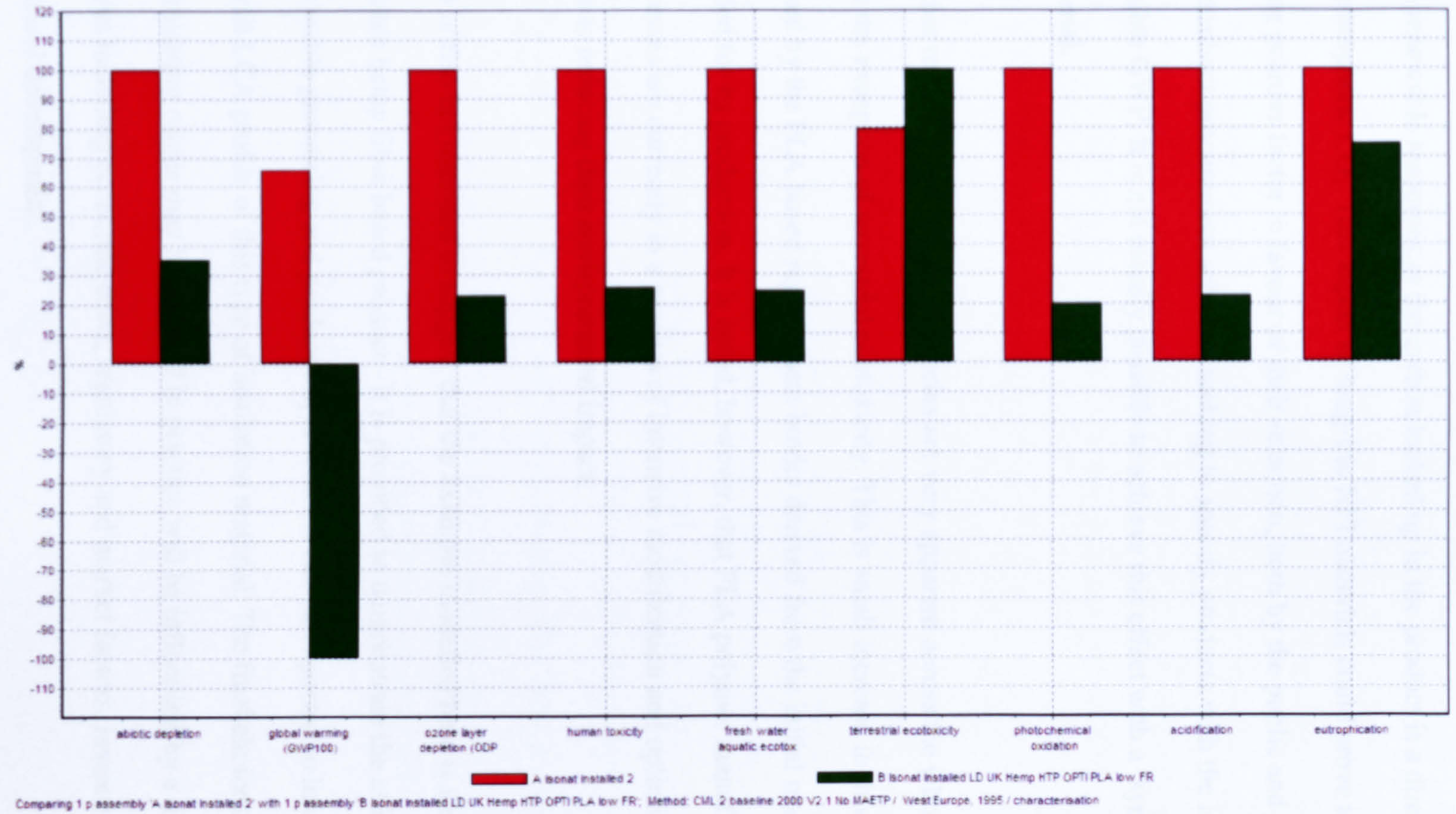


Figure 39 Graph to show the effect of a near future combination of optimization processes

What is particularly noticeable in Figure 39 is the very large reduction in GWP and the products' potential to have a substantial GWP benefit. This effect is only possible with renewable resources as the carbon locked up in the product is a direct reduction in atmospheric CO_2. This aspect of long-life NFI materials could prove to be a very strong positive factor in favour of their selection, both by the public and via government procurement schemes seeking to specify products with the lowest possible GWP. It is not usually possible to achieve this effect with a 'synthetic' material.

Further reductions in impact categories are very apparent across the whole profile with the exception of terrestrial ecotoxicity. This is small increase in this category is caused by the PLA based replacement binder derived from the initial maize farming needed for its production. It is noted, however, that PLA polymer manufacturing processes are currently in a process of intensive modification and optimisation with a view to reducing their environmental impact.

This is also not intended to suggest that the example modelled here is the 'best' possible hemp fibre based product - it is provided to demonstrate the effects that reasonable processing and product improvements can be expected to have on the overall LCA profile of this type of insulation material. The final choice of which optimisation routes may be adopted in practice will be influenced by a diversity of factors including economic costs, regulatory and market factors, investment and technical development.

4.7.8 Other Comparable Functional Units

Although they are commonly used in cold roof type installations, both Isonat and Thermafleece are supplied in the form of a semi rigid "batt". This allows them to be used in a number of different applications including sarking, timber frame stud walls and lining "warm roof" spaces. It is thought that around 50% of the Isonat product is used for wall insulation rather than in cold roof situations (Newman, personal communication). This is based on the figure that half of all Isonat sales are in the form of 60 cm widths as oppose to the 40 cm widths commonly used in "between rafter", roofing situations.

Equivalent batts are produced by many "conventional material" insulation producers and are in general much higher in density than their "roll" equivalents. As such a comparison using the functional unit of a batt will no doubt affect the impact of any comparative conventional materials studied. This calculation was not however undertaken as it was outside the Functional Unit chosen in the present comparison for which the selected materials represent current practice. This issue has been raised here to stress the importance of clearly recognising limitations imposed by the assumptions and system boundary decisions made in this and indeed any other LCA study. This is also suggested as an area for further work.

4.8 Conclusions

Highlighted as part of the sensitivity analysis, was the issue of standardising secondary dataset usage across all products considered. This was deemed necessary as differently produced secondary datasets appear to present different impacts for the same or similar materials and processes. Though the use of similar secondary data was maintained within the natural fibre insulation product LCAs (*i.e.* BUWAL and Ecoinvent), it is apparent that similar datasets were likely not to have been used in the aggregated benchmark datasets. Though this does not invalidate any comparisons it does raise the point that a great deal of consideration should be used when doing so. An understanding of the differences presented and consideration as to whether they are inherent to the products or caused by the different datasets used in there production is required. It is suggested that some of the CML baseline impacts displayed can be compared with more confidence than others. It is as such noted that taking the results presented here for commercial product comparisons is not recommended.

From the marginal analysis it was shown that both of the NFI products studied shared similar environmental burdens from the polyester binders and the direct and indirect use of fossil resources. The comparatively high use of fossil fuels is seen as an inherent problem with any smaller scale manufacture. As part of the optimization study of a hemp-based product the use of larger scale processing was shown to vastly reduce this energy usage. The results of which also showed negative impacts in the products' global warming potential, because the carbon sequestered by the material was found to be higher than that which would be emitted during the materials' production. The larger scale machinery studied was that of standard technology, still on a relatively small scale to which the benchmark product was produced. It is thought that use of larger scale or bespoke machinery, after a period of development, could hold the key to even greater reductions.

4.9 Recommendations for Further Work

It is recommended that entire and impartial data collection is carried out for such a future study. It has been highlighted many times throughout this study the use of secondary data drastically diminishes the reliability of the finished LCAs. This makes un-biased comparisons between them extremely difficult especially when comparing against aggregated datasets that may or may not include the use of different secondary datasets.

In a more commercial sense, further work studying reduced energy technologies is highly recommended in order to realise the potential of natural fibre products as shown in the optimization study of this report. Though this recommendation is made with reference to insulation products it is thought that a great deal of other renewable material based products would benefit from this work.

Part 2

Moisture Sorption in Natural Fibres

5 Literature Review

5.1 Introduction

A major conclusion from the LCA work in Part 1 of this study, was that the assumptions regarding the *in situ* performance of the insulation materials studied, could have a large effect on the LCA outcome if they are incorrect. The example given previously was that of *in situ* "sagging", which could potentially cause a reduction in thermal efficiency. Due to the large quantity of energy normally saved through the use of insulation, any small reduction in its performance can have a large effect on a ***cradle to grave*** LCA. It was also shown that such a change in the *in situ* performance could have more of an impact than the initial production of the material. As such, work in this area is of importance if more robust LCAs are to be produced.

Due to a lack of current data and time constraints of the study it was not possible to study the effects of *in situ* sagging. It was however identified that there is a current lack of understanding regarding the effect of moisture sorption regarding the performance of natural fibre insulation materials. As such a study of this was chosen as it was considered to be a valuable area of further work.

It is the aim of this second part of the overall study to gain a better understanding of the relationship between natural fibres and water vapour in order to understand how this may affect the products' performance and thus overall environmental impact.

5.2 Moisture and Insulation

As discussed by Al-Homond (2005) moisture transfers into the building structure from many sources. If enough moisture accumulates in the building envelope and cannot escape, it becomes a good environment for mold, mildew, and other moisture-related problems. If moisture penetrates into building thermal insulation it will cause it physical damage and will adversely impact its performance by increasing its thermal conductivity.

The level of damage caused by moisture or what material may be affected, was not discussed by Al-Homond (2005). However, Padfield (1998) has shown that the addition of moisture in a flax based natural fibre insulation material did not reduce the materials' insulation property (*i.e.* did not increase its thermal conductivity) until very near or actual saturation (99% RH and above) is achieved. This was revealed by the conduction of experiments to study the effect of varying atmospheric moisture across a "hot box" style thermal conductivity experiment. It was also shown by Padfield (1998) that at this near saturation point, the effectiveness of mineral fibre insulation material is also reduced by the same degree. As such this finding would in effect not change any material ranking in a comparative LCA such as that shown in Part 1.

In an experiment conducted by Huw Jenkins at Cardiff University (Jenkins, Unpub.), it was also shown that there was no significant overall difference in thermal conductivity between a flax based natural fibre insulation material and a mineral wool material, after an *in situ*, year long experiment. There was however a notable difference in how the insulation behaved. It was noted that the standard deviation of the RH ***within*** the space that the flax insulation occupied was notably lower than that of the mineral wool.

5.3 Moisture sorption of plant fibres

A large proportion of plant fibres are derived from polymer structures based on saccaride molecules. The large amount of available OH groups on such molecules and the porous nature of the fibres, make them capable of acquiring a relatively large amount of water. It is this plant fibre structure and its interaction with water vapour that will be described here.

5.3.1 Composition of Lignocellulosic plant fibres

In this section, using the example of wood fibres, the production of the main plant fibre components is first described. The physical composition of plant fibres is then further described with the use of diagrams to "zoom in" to the cell in order to aid visualisation of the role played by the chemical components in the complex multi-layered structure involved. The proportion of these chemical constituents encountered in varied natural fibres is then presented.

5.3.1.1 Plant fibres at the molecular level

Glucose and other sugars are produced by plants by means of photosynthesis. These sugars join to form the molecules that are the building blocks of the plant cell wall structure. The most important of these molecules in terms of fibre strength is that of cellulose. Cellulose is derived from glucose units which are linked to form long straight molecules some 8000 glucose units long. These β-D-anhydroglucopyranose ($C_6H_{12}O_5$) monomer units are rotated through 180° alternately along the molecule length resulting in a straight chain. These cellulose molecules lie in parallel to form a crystalline structure with neighbouring molecules running in opposite directions in order to facilitate chemical bonding between the chains. This crystalline structure is surrounded by a non-crystalline sheath composed mainly of lignin. The lignin acts as a matrix and the hemicellulose is an interfacial coupling agent.

The cell wall is made up of millions of microfibrils arranged into ordered layers. Notably in these layers the microfibrils are wound at different angles. The most important of these layers is the S_2 layer. It is generally the thickest layer and also the angle of the microfibrils, *i.e.* the microfibril angle (MFA), is closest to being parallel to the length of the cell. This arrangement provides the most (longitudinal) strength (Desch 1981). An overview of this structure is shown in Figure 40 below.

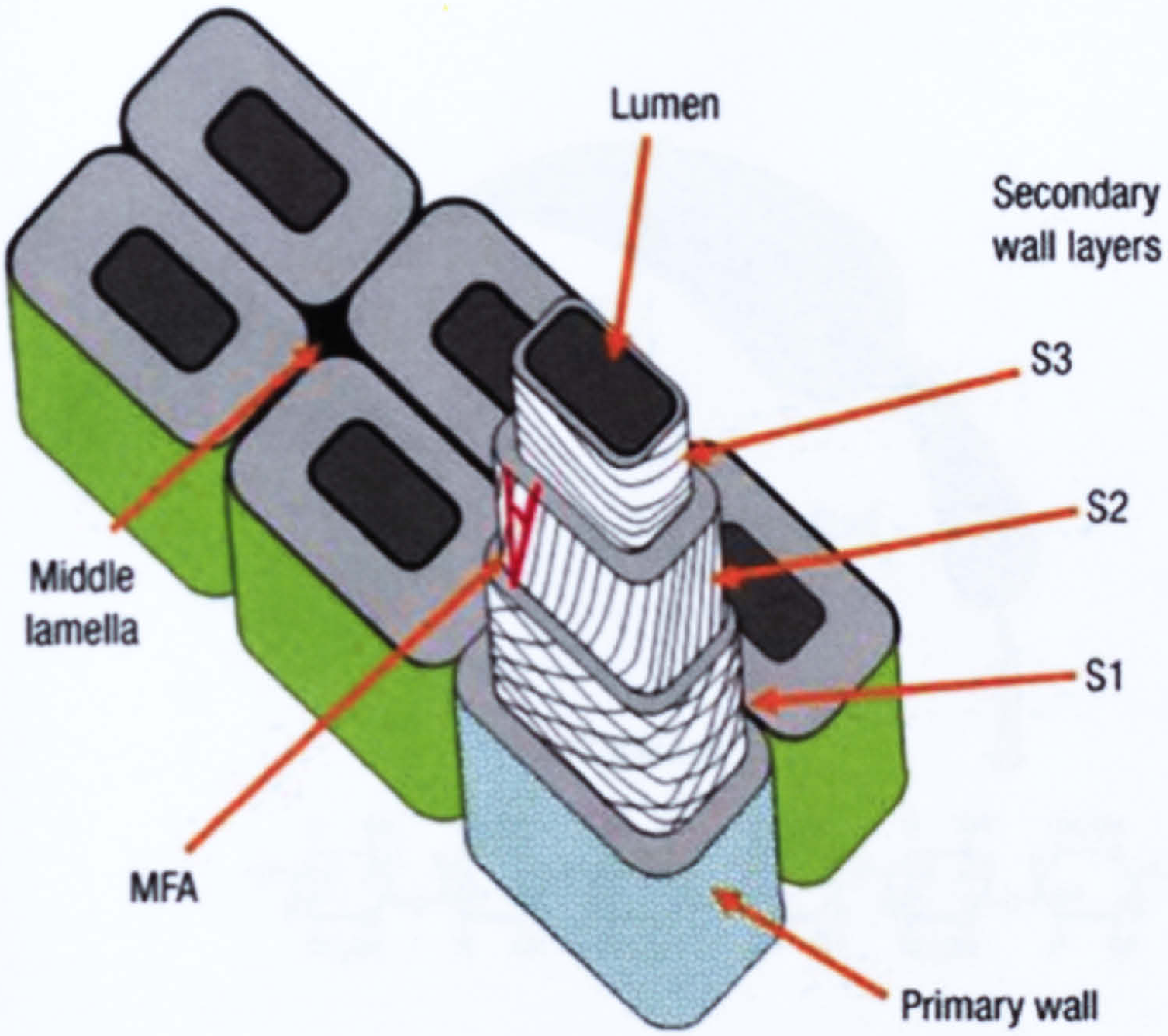


Figure 40 a drawing to show the components of the wood cell wall, as presented in Kretschmann (2003).

In Figure 40 the foremost cell has been sectioned in order to show the layered structure characteristic of each cell, comprising the primary wall, the three secondary wall layers (S1, S2, S3) and the lumen. The grey lines in the secondary walls layers represent idealized cellulose microfibrils. The cellulose microfibrils in the secondary layer appear twisted with respect to the cell's vertical axis. (Kretschmann, 2003).

A closer look at this cell wall structure in Figure 41 (though vastly simplified) shows the positioning of the previously described crystalline cellulose within the Microfibril. It also shows how this relates to the composition of fibrils and their positioning in the S2 layer. Figure 41 also shows the arrangement of the alternately rotated glucose units in the cellulose structure and their OH (hydroxyl) groups.

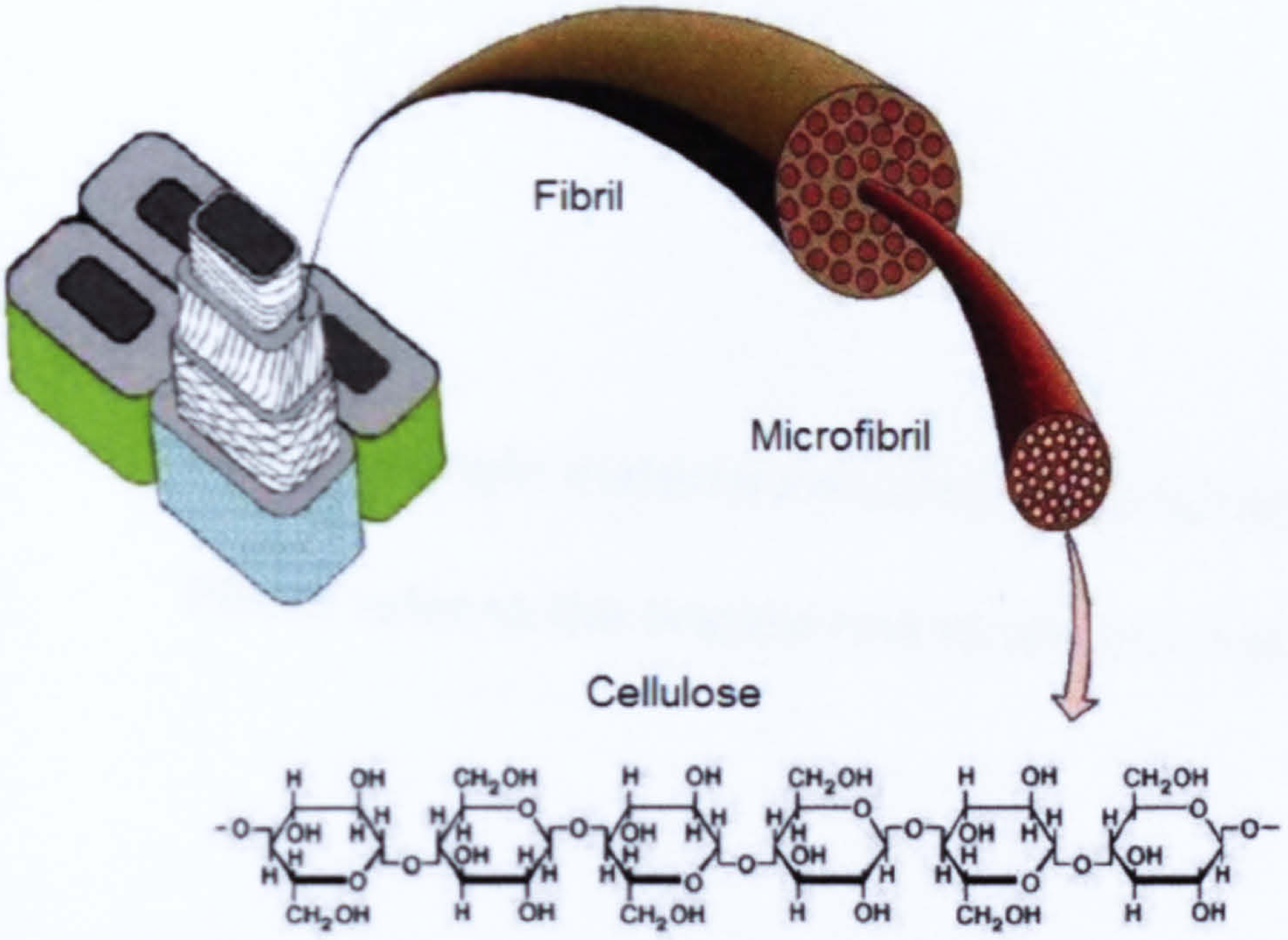


Figure 41 a drawing to show the arrangement of cellulose in a microfibril, its positioning (surrounded by hemicellulose and lignin) in a fibril, shown extending from the S2 layer of wood cell wall. Adapted from Kretschmann (2003) and Moore et al (1998).

A more technical representation of a microfibril cross section is given in Figure 42. This shows the arrangement and approximate scale of the crystalline cellulose structure surrounded by a layer of hemicellulose and then lignin.

5.3.2 Chemical component proportions of different plant fibres

As presented in the previous section, the main constituents of the cell wall are that of cellulose, hemicellulose and lignin molecules. The occurrence of OH groups or hydroxyls on these molecules (that can be seen in Figure 41 on the cellulose component of the microfibril) is very important in determining many natural fibre properties. The hydrogen bonding interactions between molecular components in the cell wall will, for example, contribute to the strength and dimensional stability properties of the fibre. The amount of OH groups varies between the molecular groups mentioned. As such, the ratios of these molecular groups will affect the overall fibre properties.

The proportion of the chemical constituents (and their arrangement) varies between differing plant fibres which gives rise to different physical properties in both the plant and its' extracted fibres. For example stiff, lignified coir fibres are suitable for brush bristles whereas the relatively highly cellulosic hemp fibres were traditionally used for making rope due to their strength and flexibility. This variation in physical properties occurs not only between plant species, but also between different varieties and even through changes in agronomic practices alone. For example, high lignin contents are generally found in late harvested flax fibres reducing their suitability for many textile products (Norton *et al,* 2006).

As described by Hill (2006), the OH groups are also responsible for the absorption of moisture. As such the availability of the OH groups will thus affect the moisture sorption of a given fibre. The cellulose core of the micro fibril provides strength due to its linear and crystalline structure. The OH groups on these particular molecules are involved in hydrogen bonding between the cellulose polymers. As such these molecules are inaccessible to sorbed water molecules because the breaking of large numbers of H-bonds to allow ingress is energenetically unfavourable. Hemicellulose is similar to cellulose in that it possesses a large number of hydroxyl groups, however far less of these are used in hydrogen bonding to other cell wall polymers (which provides a much "looser" and less organised structure than the crystalline cellulose). Hence a large proportion of the OH groups on the hemicellulose are initially accessible to water molecules. An amorphous structure is also exhibited by the lignin component and so is also involved with water interactions, but as it possesses a lower OH to carbon ratio it is considered less important with regard to water absorption.

In order to show how these chemical components vary between different plant fibres the chemical constituents of a selection of different fibre types are presented in Table 12.

Table 12 The approximate chemical constituents of a selection of different fibre types From (a) Bledzki et al, 1996 (b) Anon, 1983 in Kymalaien and Sjoberg, 2007 (c) Shawakataly, 1999 and (d) EURATEX (2000) in European Commission (2001).

Fibre type	Cellulose	Hemicellulose	Lignin	Pectin	Extractives
Flax (a)	71	18.6	2.3	2.2	1.7
Hemp (b)	67	16	3	1	0.7
Jute (c)	69.7	12.6	13.8		2.2
Coir (c)	47.3	15.2	31.4		4.2
Cotton (d)	96			1.2	2.8

5.4 Water sorption in plant fibres

In order to understand the relationship between water and plant fibres it is first necessary to understand the phases of water as presented here.

5.4.1 Phases of water

Water can exist in three general states or phases – solid (ice), liquid, or vapour depending on the temperature and pressure to which it is exposed. In general this study is concerned mainly with water vapour and to a lesser extent liquid water and its relationship with plant fibres. The primary difference between the liquid and vapour state is the spacing between the molecules. In the liquid state the molecules are sufficiently close to each other so that appreciable forces of attraction and repulsion exist among them. The individual molecules are constantly vibrating around a region of equilibrium where the force between adjacent molecules is zero. If a molecule attains enough energy it will escape from the other (liquid) neighbour molecules and become a vapour molecule. Because of their high kinetic energy such molecules will exert a pressure against an enclosure; this is called the ***vapour pressure*** of the water. The higher the temperature of the water the greater will be the number of vapour molecules and therefore the greater will be the vapour pressure of the water (Skaar 1964).

The distance between water vapour molecules is from 12 to 60 times larger than the spacing of liquid water molecules when the air is saturated (over the temperature range from 0°C to 100°C). When the vapour pressure is lower than saturated at any temperature, the spacing is even further apart.

In most circumstances, the atmosphere is not saturated. The actual vapour pressure p is lower than the saturated vapour pressure p_0. The air ***humidity*** as it is known is often measured in terms of the partial vapour pressure h, which is defined as the ratio of the existing vapour pressure p to the saturation pressure p_0 (*i.e.* p/p_0). The relative vapour pressure (h) is dependant on the vapour pressure (p) and also the temperature, since this determines the value of p_0. In a room for example, the actual vapour pressure tends to remain constant throughout the room but the temperature may fluctuate considerably from one location to another. For example, between a cool window and a radiator the temperature can vary by several degrees C. Therefore there will be wide variations in ***relative humidity*** (RH), the relative vapour pressure h multiplied by 100 percent, as this is dependent on the saturation vapour pressure which varies with temperature. If the temperature of a room or object is particularly low, the saturated vapour pressure will also be lowered. As such there will be a temperature at which moisture will begin to condense from the atmosphere onto an object that is colder than its surroundings. The temperature at which this occurs is called the dewpoint temperature T_d (Skaar 1972).

5.4.2 Sorption of water

Absorption is "the take up of a liquid by a porous solid within its gross capillary structure as a result of surface tension forces" (Stamm, 1964). It can occur in capillaries large enough to be visible without magnification. It is accompanied by only a limited reduction in vapour pressure of the liquid. In other words, the energy required to evaporate an absorbed liquid is only slightly greater than that required to evaporate the liquid from an extensive flat surface. ***Adsorption***, defined in Stamm (1964) however, "is the intimate take-up of a gas, a liquid from the vapour phase, or a solute from solution by a fine powder, a porous material, or a swelling gel substance" In many cases the take-up is only one molecule thick, *i.e.* monomolecular. When this uptake is polymolecular, the uptake rarely exceeds a layer of ten molecules thick. Considerable adsorption can occur at low vapour pressures which indicates that the attractive force of the ***adsorbent*** (*e.g.* fibre) for the ***adsorbate*** (*e.g.* water vapour), may be considerably greater than the attractive force of the adsorbate for itself (Stamm, 1964).

The previously mentioned mono-and poly-molecular layers of water are bound by means of hydrogen bonding as opposed to being firmly held by covalent bonding to the fibre cell wall. Such covalent bonding would occur when an adsorbate reacts chemically with the adsorbent. This is known as ***chemisorption***.

It is believed that water adsorbed beyond the monomolecularly held water, from 20% RH to at least 90% RH is polymolecularly held in solid solution. This is not thought of as true capillary absorption as such pre-existing capillaries are thought to provide only 2% of the cell wall volume, as such this adsorption is thought to occur in transient capillaries or spaces that only occur with a relative vapour pressure of 0.9 (*i.e.* 90% RH) or more (Stamm, 1964). The theoretical types of adsorption would occur at the relative humidities displayed in Figure 43.

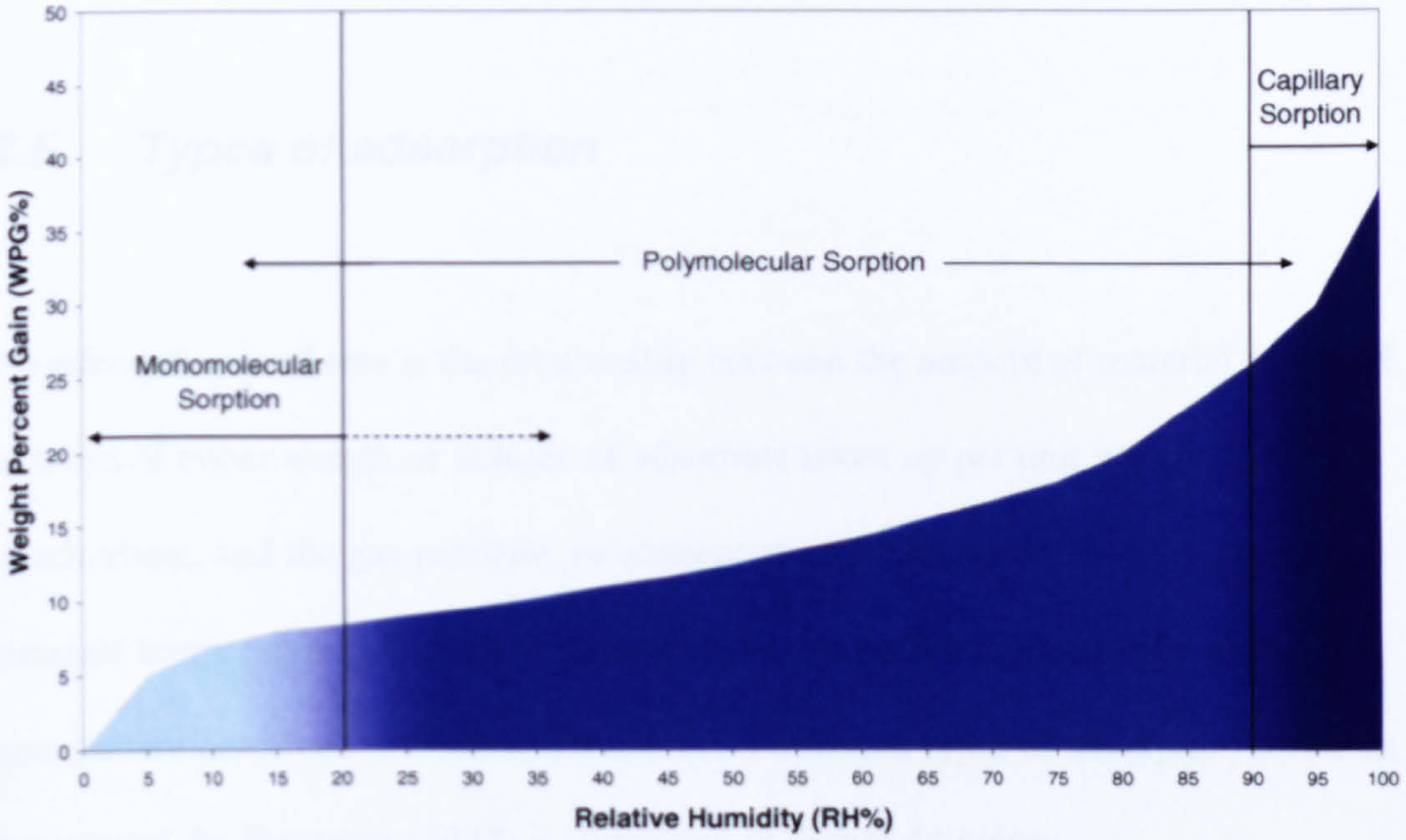


Figure 43 the theoretical stages of adsorption and the mechanisms used at differing relative humidities.

It should be noted that Figure 43 is only a rough presentation of general theories and there is believed to be a great deal of overlap between the types of sorption especially between mono- and poly-molecular sorption.

Plant fibres have a large surface area for water to be adsorbed onto. For example 1 cm^3 of wood (with a specific gravity of 0.4) will have an internal, microscopically visible capillary surface of some 870 cm^2 as opposed to the 6 cm^2 surface area of a 1 cm^3 metal cube. It is important to note that the grinding of a porous material such as wood will only slightly increase the available surface area and as such the natural internal surface is available to the adsorbate, even in sizable pieces, if sufficient time is allowed to attain equilibrium (Stamm, 1964). As water is adsorbed by a natural fibre it swells the fibre as it enters the cell walls. This adds its own volume to the volume of the fibre by forming a ***solid solution***.

5.5 Types of adsorption

An ***adsorption isotherm*** is the relationship between the amount of material adsorped, in terms of either weight or volume of adsorbate taken up per unit weight or volume of adsorbent, and the gas pressure, or concentration of adsorbate in solution at a constant temperature. Methods of measuring the adsoption isotherm of a given material are described in Section 5.9 and the 5 different types of adsorption isotherm recognised by Brunauer (1943) is illustrated in Figure 44 below.

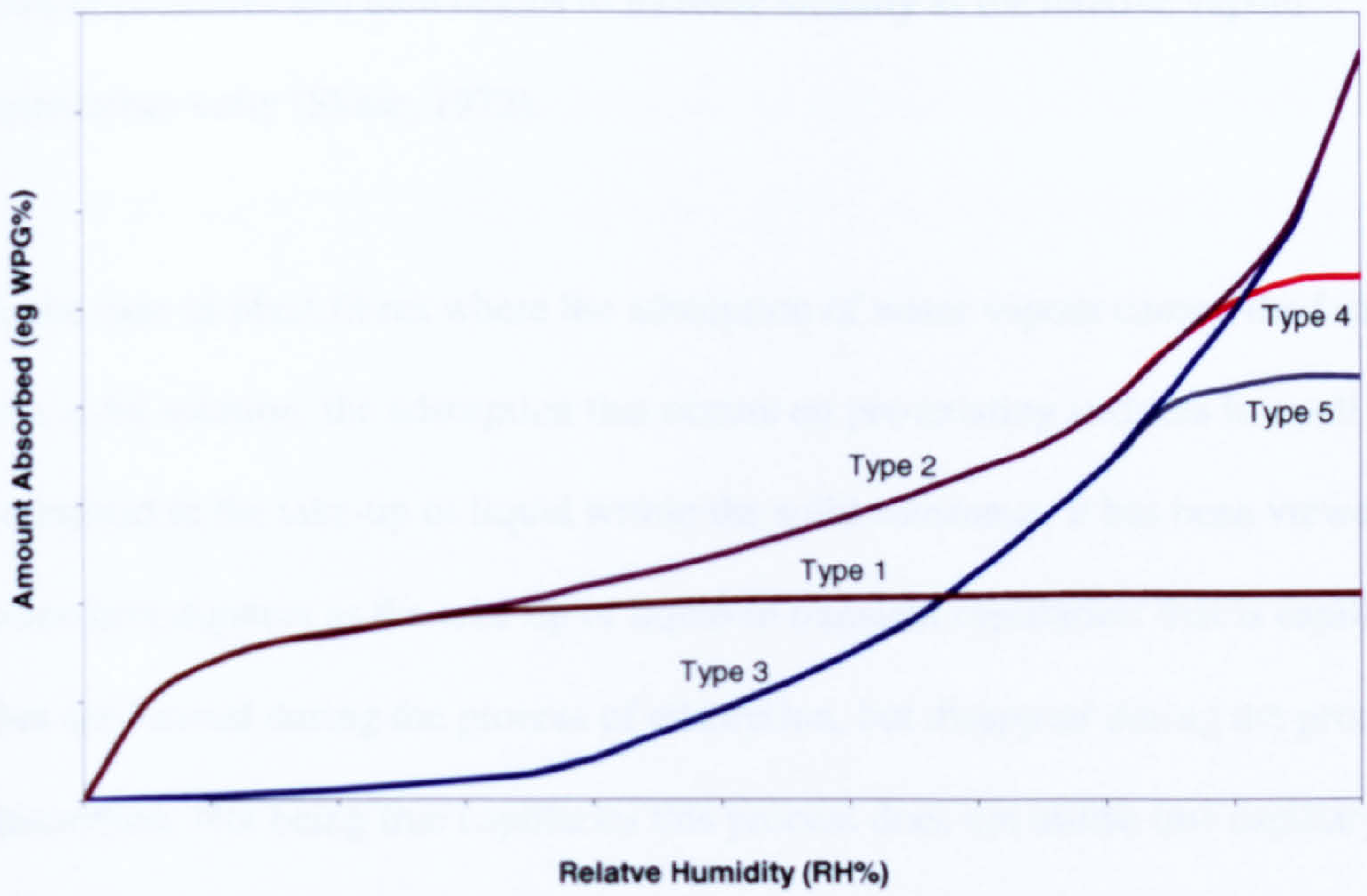


Figure 44 the five types of physical adsorption isotherms identified by Brunauer (1943). Note that the amount adsorbed is shown purely as an example to display the shape of each type of curve and not as a strict reference.

In terms of lingocellulosic materials, only the type 1 and 2 adsorption curves are thought to occur. As such the type 3, 4 and 5 curves are not described here.

Type 1 adsorption, or "Langmuir adsorption" describes monolayer adsorption. It applies to the adsorption of gases above the critical temperature (where the gas cannot be condensed at any pressure) on any solid surface. It also applies to adsorption from solution on all types of solids. An adsorbate that reacts chemically with the adsorbent *i.e.* during chemisorption would always exhibit this isotherm.

Type 2 adsorption is a sigmoidal (S –shaped) type of adsorption and it has been described as always polymolecular. It follows the type one isotherm at low relative vapour pressures and then begins to increase steadily as the relative vapour approaches unity (Skaar, 1972).

In the case of plant fibres where the adsorption of water vapour caused the formation of a solid solution, the adsorption that occurs on pre-existing surfaces is small compared to the take-up of liquid within the solid substance. It has been viewed by some investigators as the take-up of liquid in transient capillaries: that is capillaries that are formed during the process of adsorption, but disappear during the process of desorption. Not being true capillaries this process does not utilise true capillary condensation filling as a result of normal surface tension forces which involve the replacement of a solid-air (or solid vacuum) interface with a solid-liquid-solid interface. This filling of pre-existing microscopically visible capillaries only occurs in plant fibres above 90% RH (Stamm, 1964).

5.6 Fibre saturation point

The term "fibre saturation point" (FSP) expresses the maximum amount of cell wall water that can be taken up from the vapour phase at a given temperature by a unit weight of a plant fibre or component, As such it is the water content of the plant fibre when the relative humidity in the surrounding atmosphere is exactly 100% (*i.e.* dew point). When this point is reached further water adsorption can only occur externally to the cell wall.

Though considerable difficulty has been experienced in establishing both experimental measurement and definition, the concept has proved useful in the study of both theoretical and practical aspects, regarding the interaction of water with plant fibres (Browning, 1963).

5.7 Sorption hysteresis

The amount of water held by cellulosic materials is not only dependant upon the equilibrium relative vapour pressure, but is also dependant on the direction from which the equilibrium is approached. This phenomenon is known as ***sorption hysteresis***. The amount of water ***ad***sorbed from the dry condition is always ***less*** than the amount retained on ***de***sorption for any given RH, as shown in Figure 45.

It was previously believed this phenomenon was caused by a lack of attainment of true sorption equilibrium. This was disproved by greatly extending the sorption time. It was also believed that the presence of air was responsible for hysteresis, but several investigators were unable to reduce the hysteresis effect by making their sorption measurements in sealed evacuated systems at gas pressures as low as 0.001 mm of mercury. As 99.9% of the adsorption by a plant fibre (or swelling gel) results from the formation of solid solutions, they are unaffected by the presence of air, *i.e.* the sorption occurs involving the replacement of solid-solid interfaces by solid-liquid-solid interface as per a type 2 sorption (Stamm, 1964).

A favoured explanation for sorption hysteresis is given by Urquhart (1958) is the change in ***availability*** of the polar hydroxyl groups of cellulose, which are believed to bond the water by hydrogen bonding. In the original water soaked condition (as they would be in the growing plant), the OH groups of cellulose and lignin are almost entirely satisfied by sorbed water. When a plant fibre is dried, a number of hydroxyl groups are freed, and as shrinkage occurs, they are drawn closely enough together, to bond to each other. Thus upon subsequent adsorption, part of the hydroxyl groups of the fibre that are bonded to each other are not freed for water adsorption, thus resulting in a decreased adsorption.

Another popular theory was presented by Barkas (1949), where it was shown on theoretical grounds that hysteresis may also be due to stresses set up as a result of swelling pressure forces in a wood or cellulose gel. This is due to the fact that the materials studied are not perfectly elastic and as a result are capable of assuming permanent deformations under stress.

Neither of the popular theories presented here, or any the several others regarding hysteresis, appear to have been unequivocally proven or disproved to date. It may indeed be that the hysteresis effect observed is an effect of a combination of many mechanisms but it would appear that it is not fully understood.

5.8 Effect of temperature on sorption.

It has been found by a number of researchers that when "sorption" experiments (not necessarily distinguishing between ***ad*** or ***de***-sorption) are conducted at a range of temperatures, a lower moisture content is shown at higher temperatures, for the same relative vapour pressure (or RH). For example as presented in Skaar (1972) in Figure 46 below.

h

Figure 46 sorption isotherms at three different temperatures showing EMC (%) against relative vapour pressure h, (Skaar, 1972).

It is well documented in wood science literature (Skaar 1972, Stamm 1964 *etc.*) that *de*sorption curves exhibit the phenomenon shown in Figure 46 above. It is also noted from varied (wood, textile and food) literature that this "spread" of isotherms has also been exhibited by various *ad*sorption experiments using varied plant materials, for example; wood, hemp and flax fibres (Stromdahl, 2000) flax straw and hemp stalks (and Nilsson *et al*, 2005), cotton fibre (Urquhart and Williams 1924), Jute fibre (Macmillan *et al*,1946) and tea (Arslan and Togrul, 2006).

5.9 Methods of measuring sorption isotherms

There are many methods available for measuring the sorption of water vapour by natural fibres. In general most methods work on the same gravimetric principal whereby samples of known dry weight are exposed to varied humidity levels and their weight is measured after the (ad- or de-) sorption moisture content has been given time to equilibrate. The change in weight is either studied by measurement *in situ*, or by removal from the conditioned environment and measured separately. The removal of the sample into a different environmental condition for weighing is likely to affect the results in some way as the sample starts to equilibrate with its' new surroundings. This effect can be minimised with the use of large samples and/or limited weighing times. In order to maintain the required humidity levels for such experiments, a number of different methods have been used. For example;

Aqueous salt solutions. Various known saturated salt solutions will produce an individual RH in the air above it. By enclosing samples in such an environment the sample will thus equilibrate to the known RH and the moisture content calculated when the (oven) dry weight is also known. The management and description of selected salt solutions is described in ATSM E104-85 (Anon., 1991).

Aqueous Acid concentrations. Concentrations of sulphuric acid can also be used to produce a known RH, with obvious hazards and potential damage to the fibres at high acid concentrations (low RHs) as described by Macmillan *et al* (1946). The management of such solutions is also described in ATSM E104-85 (Anon., 1991).

Monitored "air conditioning". With the advent of computerised monitoring using feedback from temperature and RH probes to determine the addition or removal of humidity, various controlled environmental condition units have been reported, such as:

- **Atomizing humidification** *e.g.* Arslan and Togrul (2006) maintained their required RHs by atomizing a blend of purified water and air into a "fog". It is worthy of note, with regard to experimental design, that in this case the use of an UV lamp positioned above the samples "to prevent microbial growth" does cast some doubt as to the actual RH surrounding the samples, especially as both the temperature and RH probes were positioned above the water atomizer the other end of the 2m long chamber.
- **Dry and saturated air mass flow.** The relative humidity can also be controlled by mixing two air lines containing dry and saturated air. With the required RH set by controlling the flow of each individual line. This is used on a relatively large scale (approx 1m^3 cabinets) by Stromdahl (2000) and on a much smaller scale in the "dynamic vapour sorption analysis" which is described in detail in Chapter 6 of this study.

5.10 Heat of wetting

An important phenomenon concerning the sorption of water is that of the ***heat of wetting.*** As previously described, considerable adsorption can occur at low vapour pressures caused by the attractive force of the fibre (adsorbent) for the water vapour (adsorbate), being considerably greater than the attractive force of the adsorbate for itself (Stamm, 1964). In all cases ***ad***sorption is accompanied by the evolution (release) of heat, *i.e.* the heat of wetting.

As part of this study it is considered that where a large quantity of fibre is used, the heat of wetting in natural fibres may have an effect on its surrounding environment. The *in situ* performance of a natural fibre based insulation material may thus be affected by this phenomenon, which may in turn have a bearing in the products LCA outcome. Therefore, a brief description of the energies involved with the sorption process is presented here before a description of the methods used to gain data regarding the heat of wetting.

The differing quantities of energy involved in this dynamic system are explained by Skaar (1972); Moisture occurs in plant fibres in three forms, analogous to the three states of water; There can be water vapour in the air spaces in the cell wall cavities, capillary or free (liquid) water in the cell cavities and hygroscopic or bound water in the cell walls. Water-vapour molecules are at the highest potential energy level, capillary-water molecules are at a lower potential energy and hygroscopic or molecules in the cell wall are at a still lower energetic state.

Continuing the analogy with regard to energetic states, the water vapour molecules in the cell wall cavities are in the same high energy state as water vapour outside the fibre. The liquid capillary-water molecules are at a very slightly lower energy level, than that of ordinary liquid water due to capillary-water attraction. This difference is normally neglected. The potential energy level of the bound water is slightly different to that of frozen (or solid state) water as the sorbed water molecules are held with ***varying*** energies depending on the fibre moisture content, whereas all the molecules in ice are in (practically) the same energy state. A diagrammatic representation of this analogy is given in Figure 47 below:

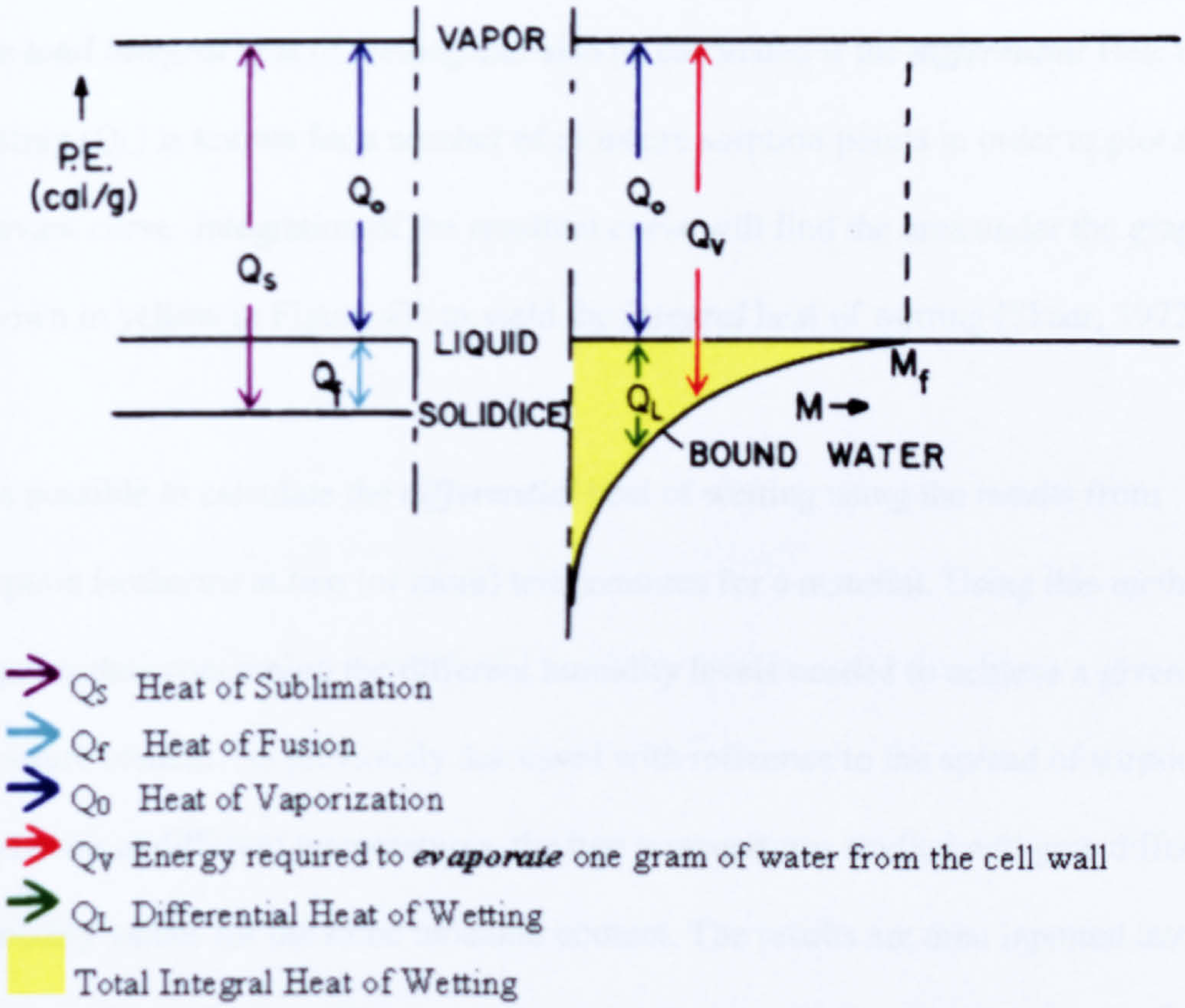


Figure 47 a schematic diagram to show the relative potential energy levels of water vapour, liquid water and bound water on the left and their analogous equivalent in a plant fibre on the right. Note the increase in energy shown by the bound water as the moisture

The difference $Q_v - Q_o$ where Q_v is the energy required to evaporate one gram of water from the cell wall and Q_o is the energy required to evaporate one gram of water from the liquid state is designated as Q_L the ***differential*** heat of wetting of liquid water by a plant fibre. Q_L is therefore the additional heat energy over and above the heat of vaporisation Q_o of free water, which must be supplied to evaporate one gram of water. This is analogous to the heat of fusion required to melt ice Q_f. The value of Q_v varies between 3470 and 2380 joules per gram of water between "ovendry" moisture content and fibre saturation point at 50°C. 2380 joules per gram of water is thus the value of Q_o (Skaar, 1972).

The ***total integral*** heat of wetting can also be calculated if the ***differential*** Heat of wetting (Q_L) is known for a number of moisture sorption points in order to plot the relevant curve. Integration of the resultant curve will find the area under the graph (shown in yellow in Figure 47) to yield the ***integral*** heat of wetting (Skaar, 1972).

It is possible to calculate the ***differential*** heat of wetting using the results from sorption isotherms at two (or more) temperatures for a material. Using this method requires data concerning the different humidity levels needed to achieve a given moisture content. As previously discussed with reference to the spread of sorption isotherms at different temperatures, the two temperatures studied will give differing humidity values for the same moisture content. The results are then inputted into a version of the ***Clausius-Clapeyron*** equation. This method is described in detail in the methodology of Chapter 7.

5.10.1 Sorption models

In order to use a given set of isotherms the equation of the sorption curve must be calculated or estimated from the experimental data points. In many cases data regarding sorption of plant fibres has been smoothed into a usable isotherm by means of the various established sorption models. These sorption models in general rely on various theories regarding the sorption of water onto the fibre. For example the Hailwood Horrobin theory calculates the sum of a theoretical mono and multi-layer curve to produce a model curve for a material where the required constants have been previously calculated from isotherm data. There are many other sorption models, such as the BET, Dent, and Le and Ly models described in Avramidis (1997) which can be used to predict sorption curves. Each model would also appear to fit data points for different materials more accurately than others, as described by Nilsson *et al* (2005) where five different models have been used to produce isotherms curves for hemp and canary grass from limited (four) data points, noting that a closer fit was exhibited by differing models for each different variety and stage of retting.

5.10.2 Heat of wetting from calorimeter

It is virtually impossible to measure the ***differential*** heat of sorption (Q_L) directly by calorimetric means, as to do so would require the addition of a small amount of water uniformly throughout a large enough sample of plant fibre such that its moisture content would remain essentially unchanged (Skaar, 1972).

However, the ***integral*** heat of wetting can be measured directly using the calorimetric method by using a sorption calorimeter. In this method a small amount of a given material is added to water in a sealed reaction chamber and the enthalpy change is thus measured. If the starting moisture content of the sample was zero, then the result will be the ***Total*** integral heat of wetting (*i.e.* the area shown in yellow in Figure 47 previously). This method has been used to gain data on the heat of wetting of various materials in the past but has also been found to be unreliable for certain materials, *e.g.* flax, due to poor mixing between water and material (Dieste, personal communication).

5.11 Conclusions

A number of water sorption characteristics have been discussed in this chapter that raise questions over the effect of moisture in the LCA of natural fibre insulation materials. The work of Padfield (1998) showed that the adsorption of water vapour does not effect the thermal conductivity in natural fibre insulation any differently to that of mineral based materials, *i.e.* no change is noted until fibre saturation point in the natural fibres (and "condensation" on the mineral fibres) has most likely occurred. Hence further studies in this area are unlikely to produce a different outcome to a comparative LCA as described previously.

However, it does appear from further review of water sorption that other characteristics may affect an LCA outcome. The most inportant of these would appear to be that of the ***heat of wetting***, as is it may be possible that the small quantities of heat evolved and absorbed during moisture adsorption and desorption, respectively, may affect the energy use in a dwelling where a large amount of material is used.

6 The use of Dynamic Vapour Sorption

6.1 Introduction

From the previous literature review in Chapter 5 of this study, it was identified that the moisture sorption of natural fibres may affect the performance of an insulation material made from them. In particular it was noted that the heat of wetting of natural fibres may affect the internal environment of a studied dwelling. As such the LCA of such material may also be affected due to this change in environment on the inhabitants, during the materials' long service time.

The use of natural fibres can effect the building environment in a number of ways, all of which may lead to a change in the "comfort" of the occupants thus affecting their potential use of ventilation and heating:

- Sorption of water vapour releases heat, some of which will enter the dwelling
- Sorption of water vapour will reduce the RH of the dwelling to some extent.
- The release of moisture from natural fibres may have a role in regulating the building temperature and humidity.

Dynamic vapour sorption analysers have been used to produce extremely accurate studies of moisture sorption in a variety of natural and synthetic materials. Many of these studies have been concerned with pharmaceutical and food industry studies, where for example the shelf life of products is often dependant on the materials' sorption of water, thus knowledge of its relation to water vapour is vital.

It was the aim of the experimental work presented in this chapter, to gain an understanding of the moisture sorption characteristics of various natural fibres. Rather than use the commonly used method of adsorption – desorption over salt solutions, this study uses a Dynamic Vapour Sorption (DVS) apparatus. This allowed for very accurate isotherms to be obtained and also allowed for these to be run at different temperatures. Since the DVS is not commonly used to calculate heat of wetting values a considerable amount of time was spent on experimental development.

6.2 Methodology

In this study the DVS analyser has been used to produce graphs of various natural fibres in order to gain a greater understanding of their atmospheric moisture sorption behaviour. An introduction to Dynamic Vapour Sorption (DVS) used in this study is presented here.

6.2.1 The Dynamic Vapour Sorption (DVS) System

In order to understand the operation of the Surface Measurement Systems® DVS a schematic diagram of the system is presented in Figure 48 below and then described.

As can be seen from Figure 48 one of the most important parts of the DVS is the Cahn® ultra-sensitive microbalance which is capable of measuring changes in sample mass lower than 1 part in 10 million. This type of microbalance has very good long-term stability and is therefore ideally suited to the measurement of vapour sorption phenomena, as the study of which may take anything from minutes to days or even weeks. The sample and reference holders that hang from the microbalance are held in a constant flow of variable and controlled water vapour. The required relative humidities are generated by mixing dry and saturated vapour gas flows in the correct proportions using mass flow controllers. Humidity and temperature probes are situated just below the sample and reference holders to give independent verification of system performance.

Both wire mesh and glass sample holders were used during the experimentation in this study with no difference in performance recorded, however due to easier cleaning of the glass sample holders they were favoured in later experimentation.

The Cahn® microbalances have occasionally been noted (by the manufacturer) to exhibit slight drift over "long" time periods if exposed to high relative humidity's. The typical size of this problem varies from balance to balance, but may typically be 10 μg over a 24-hour period of time. By flowing a purge of dry gas through the head of the balance at all times (shown in Figure 48), this drift is almost entirely eliminated (Surface Measurement Systems Ltd UK, 2003).

The main part of this unit is housed in a precisely controlled constant temperature incubator which ensures accurate control of the relative humidity generation. The whole instrument is controlled by an IBM compatible PC Microcomputer. A schematic of which is shown in Figure 49 below.

The microcomputer was interfaced to the balance control unit via an RS-232 serial link, whereas the DVS control electronics are interfaced via a National Instruments analogue/digital data acquisition card.

6.2.2 DVS Experimental

The sample holder pan was first cleaned by rinsing it in water then ethanol, then was carefully placed back on the wire hanger that extends down from the microbalance arm and the chamber and incubator closed. The balance was then tared once it has settled and the sample holder is shown to be clean and dry, which is determined by varying the RH of the chamber and noting any change in mass that may be caused by left over material adsorbing water vapour, or by water or ethanol evaporating. Taking the RH up to over 80% was used to diminish any static that may have built up.

Samples of around 4 mg were then placed into the DVS sample holder using tweezers, ensuring that none of the sample contaminated the chamber below as this is very hard to clean and may also affect results. This can be achieved by covering the aperture with a credit card sized piece of paper. It is worthy of note that large samples of up to 10 mg were initially used but were found to take over a week to analyse and so this smaller sample size was chosen as it still produced reliable results. Once the balance and environmental conditions had settled the chosen experimental program was run. In most cases a series of 5% RH increments was programmed into the data acquisition software, starting from 0% and rising to 95% then returning to 0%. This was used in order to produce the data required to calculate detailed ad and de-sorption isotherms and thus a hysteresis loop. A typical program is shown in the form of a graph in Figure 50. Note the difference in time taken to reach the chosen cut off at different RHs and the identical (very nearly horizontal) angle prior to this shown by the red mass change line.

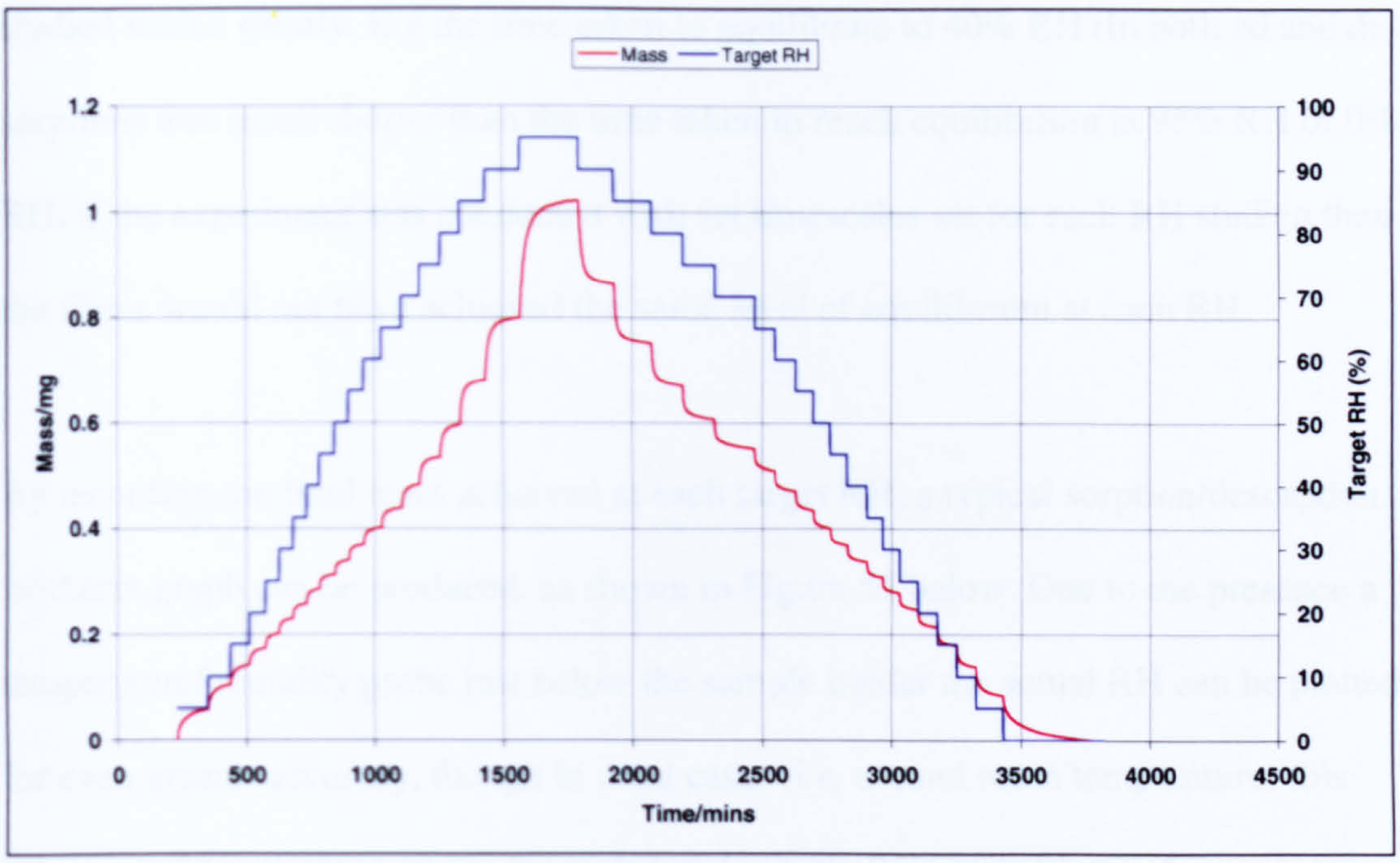


Figure 50 an example DVS mass change over time graph to represent a typical sorption/desorption profile as studied using a DVS analyser.

Time limits were not introduced for each data point, instead the DVS function of recognising the ***same rate of change in mass over time*** was used as this was thought to produce more comparable data. By allowing the DVS to calculate the same change in mass over a change in time, *i.e.* a "**dm/dt**" of 0.002%, a figure was produced for each RH studied in the experiment where a comparable change in moisture sorbtion had been achieved. This would be seen in Figure 50 as an identical angle of the individual sorption curves is shown immediately prior to the next target RH step if greatly magnified.

This was found to be a superior method compared to cutting each RH studied in the experiment off at a particular time limit. With the latter method it can only be guessed as to how near or far the sample was to equilibrium before the experiment moves on to the next RH. This could well be an important part of the methodology as it can also be seen in Figure 50 that the time taken to reach (very near) equilibrium at each RH studied varied greatly. E.g the time taken to equilibrate to 40% RH (in both ad and de-sorption) was much shorter than the time taken to reach equilibrium at 95% RH or 0% RH. If the experiment was conducted with set timescales set for each RH studied then the fibres would not have achieved the same level of equilibrium at each RH.

By recording the final mass achieved at each target RH, a typical sorption/desorption isotherm graph can be produced, as shown in Figure 51 below. Due to the presence a temperature/humidity probe just below the sample holder the actual RH can be plotted for even greater accuracy, though in most cases (*i.e.* around room temperature) this was generally not necessary as the target and sample RHs were identical.

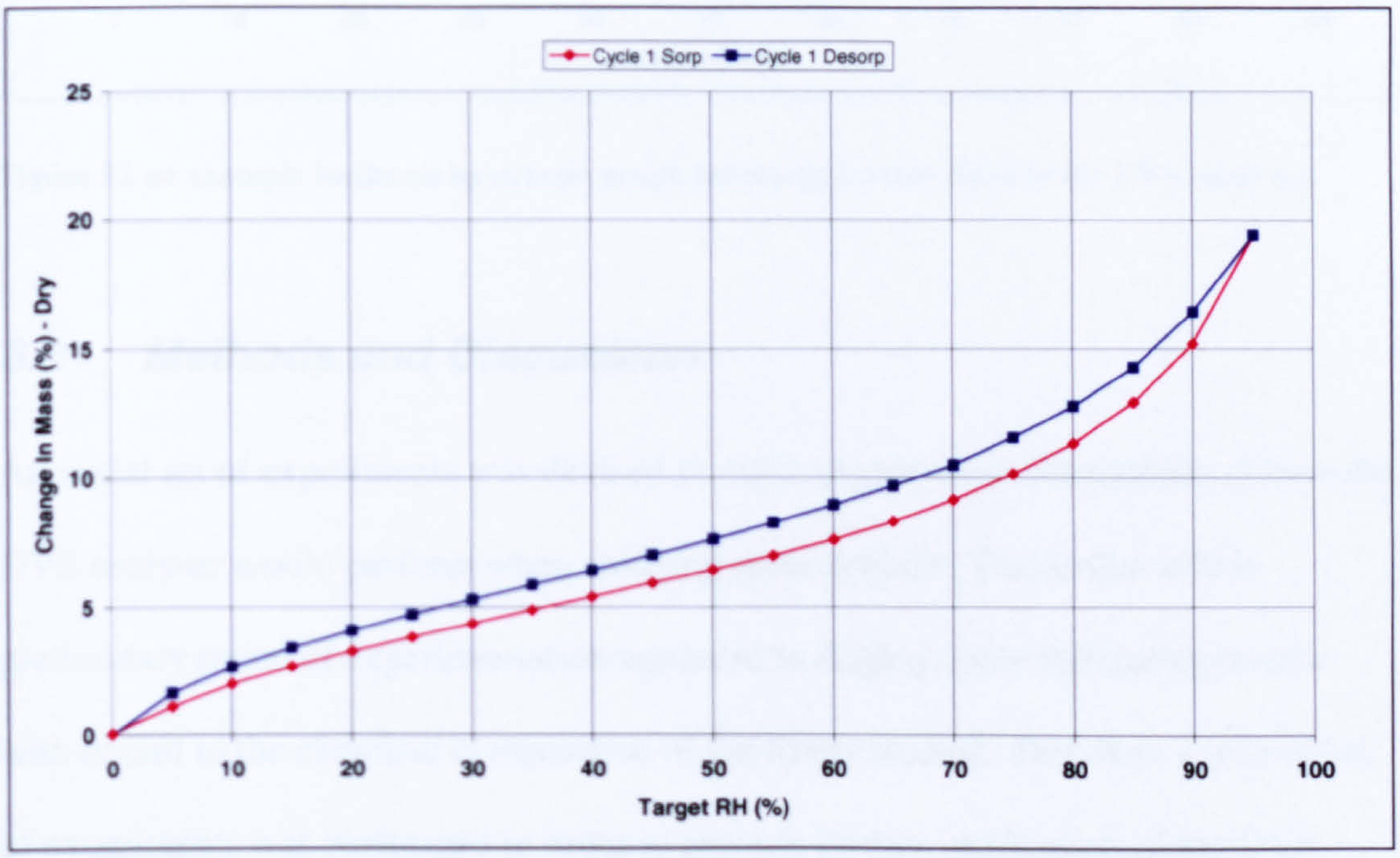


Figure 51 an example adsorption/desorption isotherm graph produced by flax fibre in the DVS analyser.

By subtracting the mass change (or weight percent gain) of the adsorption curve from the desorption curve, a graph showing the amount of hysteresis at a given RH is produced. As shown in Figure 52 below.

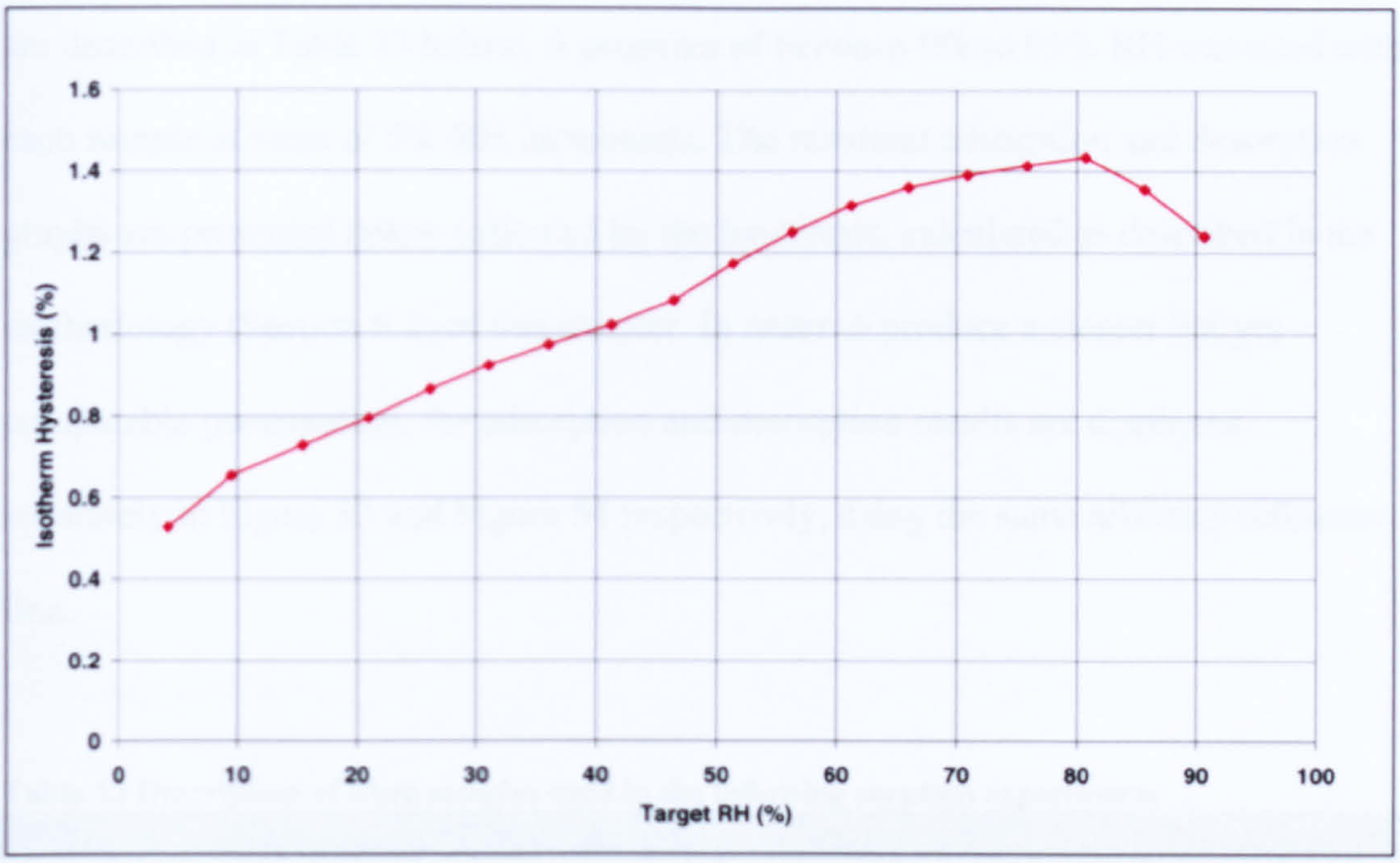


Figure 52 an example isotherm hysteresis graph produced by flax fibre in the DVS analyser.

6.3 Methods and Discussion

An initial set of experiments was devised in order to gain an understanding of how the DVS analyser would perform when studying natural fibres. The results of this preliminary round of experimentation appeared to display some interesting results with regard to the chemical composition of the fibres studied. Therefore a second set of experiments was performed in order to provide further verification of the DVS analysers' performance. The results and brief discussions thereof regarding both "experimental 1" and "experimental 2" are presented here.

6.3.1 Experimental 1

The DVS analyser was used to study various natural fibres in order to gain an understanding of their relationship with water vapour. The origin of the fibre samples are described in Table 13 below. A program of between 0% to 95% RH was used with each sample at steps of 5% RH increments. The resultant adsorption and desorption graphs are presented below followed by the hysteresis, calculated as described in the methodology (Section 6.2) of this chapter. In order to produce a clearer but yet comparable presentation, the adsorption and desorption results are displayed separately in Figure 53 and Figure 54 respectively, using the same arbitrary reference line.

Table 13 Description of fibre samples used in the following sorption experiments

Fibre	Description of fibre sample	Origin of fibre	Manufacturer /supplier
Flax	Milled pre-yarn line fibre sliver	Northern France	Saneco
Hemp	Milled short fibre tow	East Anglia, UK	Hemcore
Jute	Milled pre-yarn tow fibre sliver	India	Wigglesworth
Coir	Milled low grade wadding fibre	Unknown	Enkev
Cotton	Cosmetics grade "cotton wool"	Unknown	Boots
Sitka	Milled sample blocks	UK	Forestry Commission

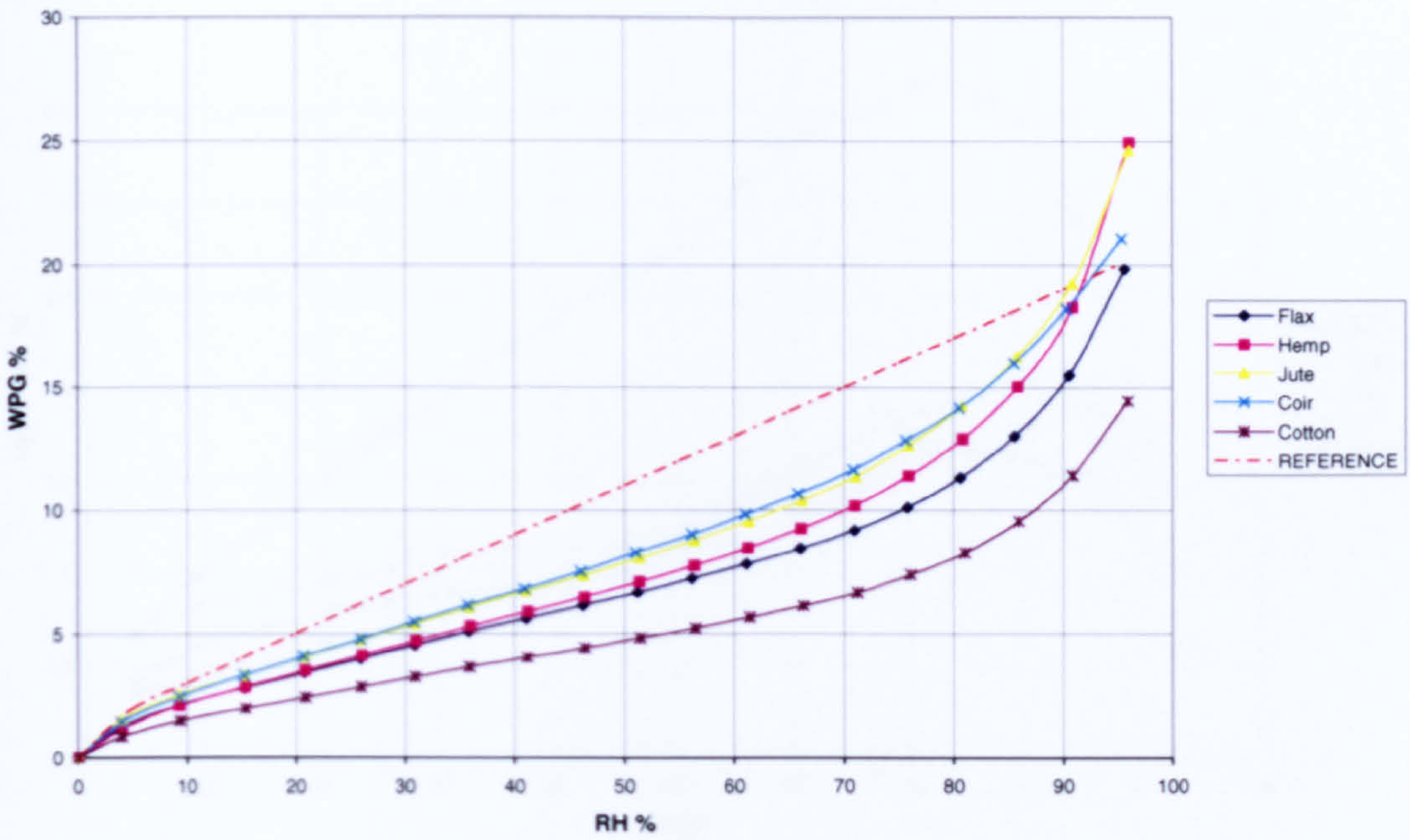


Figure 53 a graph to show the adsorption curves produced by various natural fibres studied by DVS analysis at 25°C

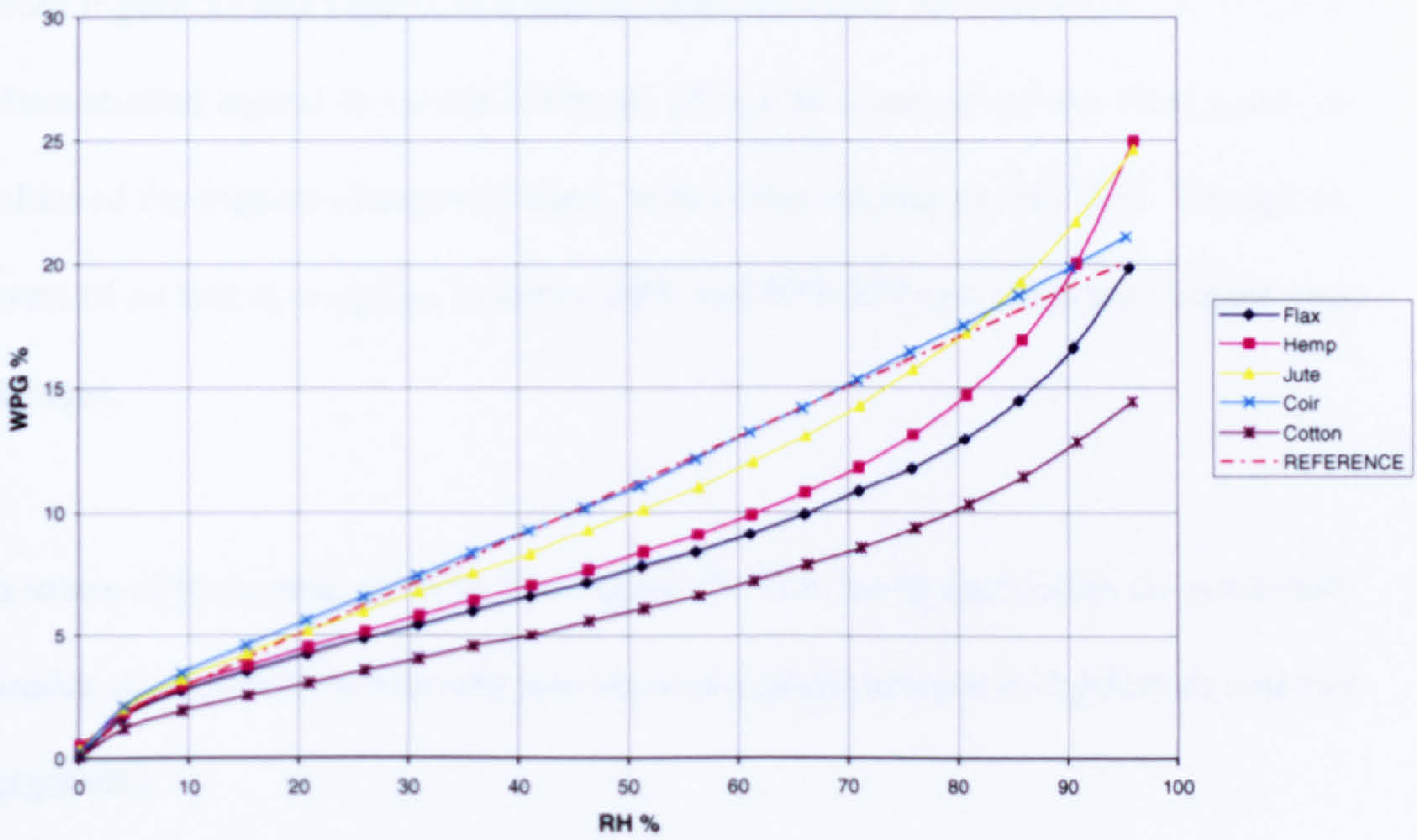


Figure 54 a graph to show the desorption curves produced by various natural fibres studied by DVS analysis at 25°C (using the same reference line as the previous adsorption graph)

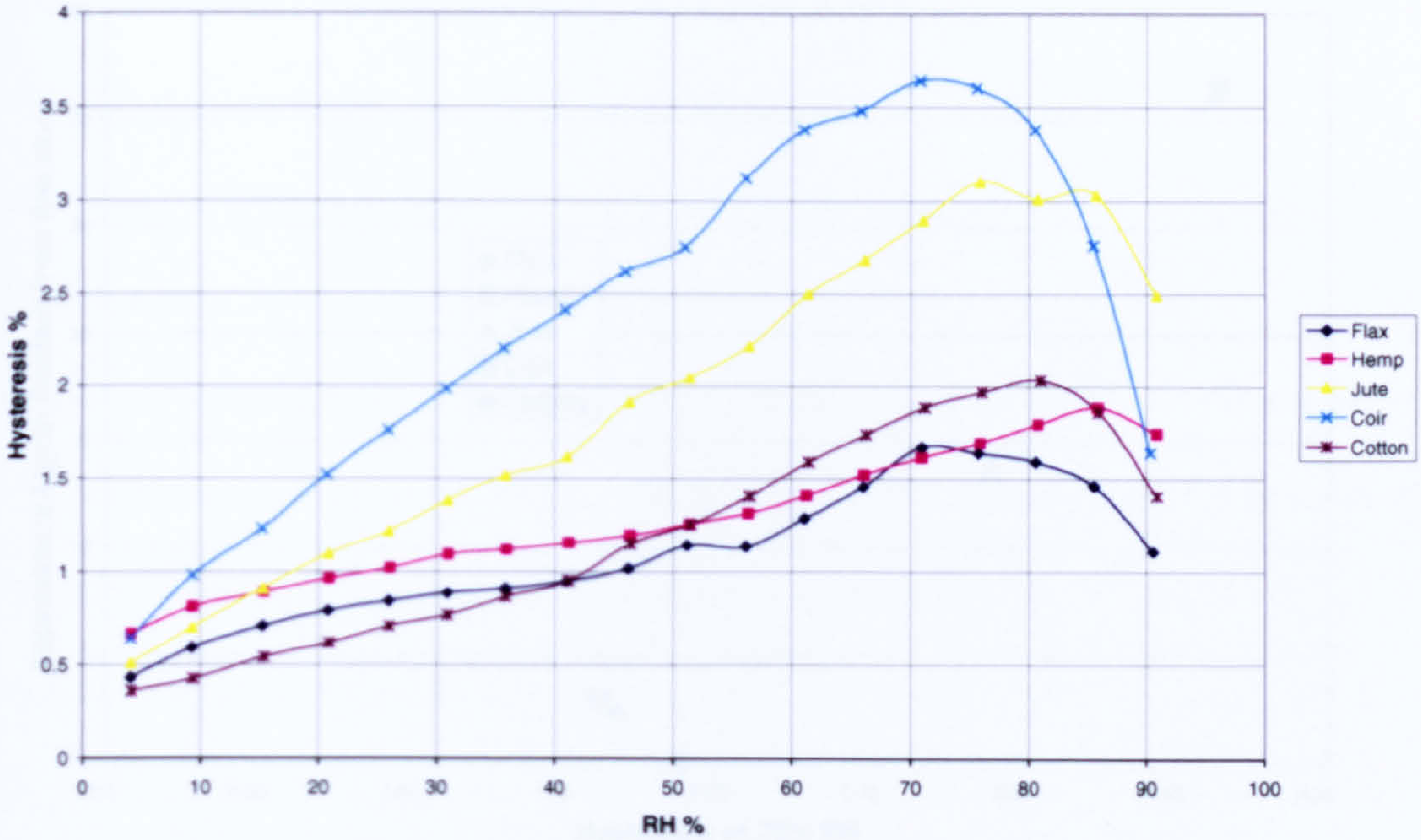


Figure 55 a graph to show the hysteresis curves exhibited by various natural fibres studied by DVS analysis at 25°C

From Figure 53 and Figure 54 it can be seen that there the different types of natural fibres studied appear to exhibit different ad and de-sorption curves. Hemp and jute achieved the highest changes in mass, with cotton displaying the least. Though in terms of ad and de-sorption between 10% and 80% RH coir possessed higher mass changes.

In terms of hysteresis, as shown in Figure 55, flax, hemp and cotton all possessed similar characteristics, whereas jute showed a larger amount of hysteresis and coir larger still.

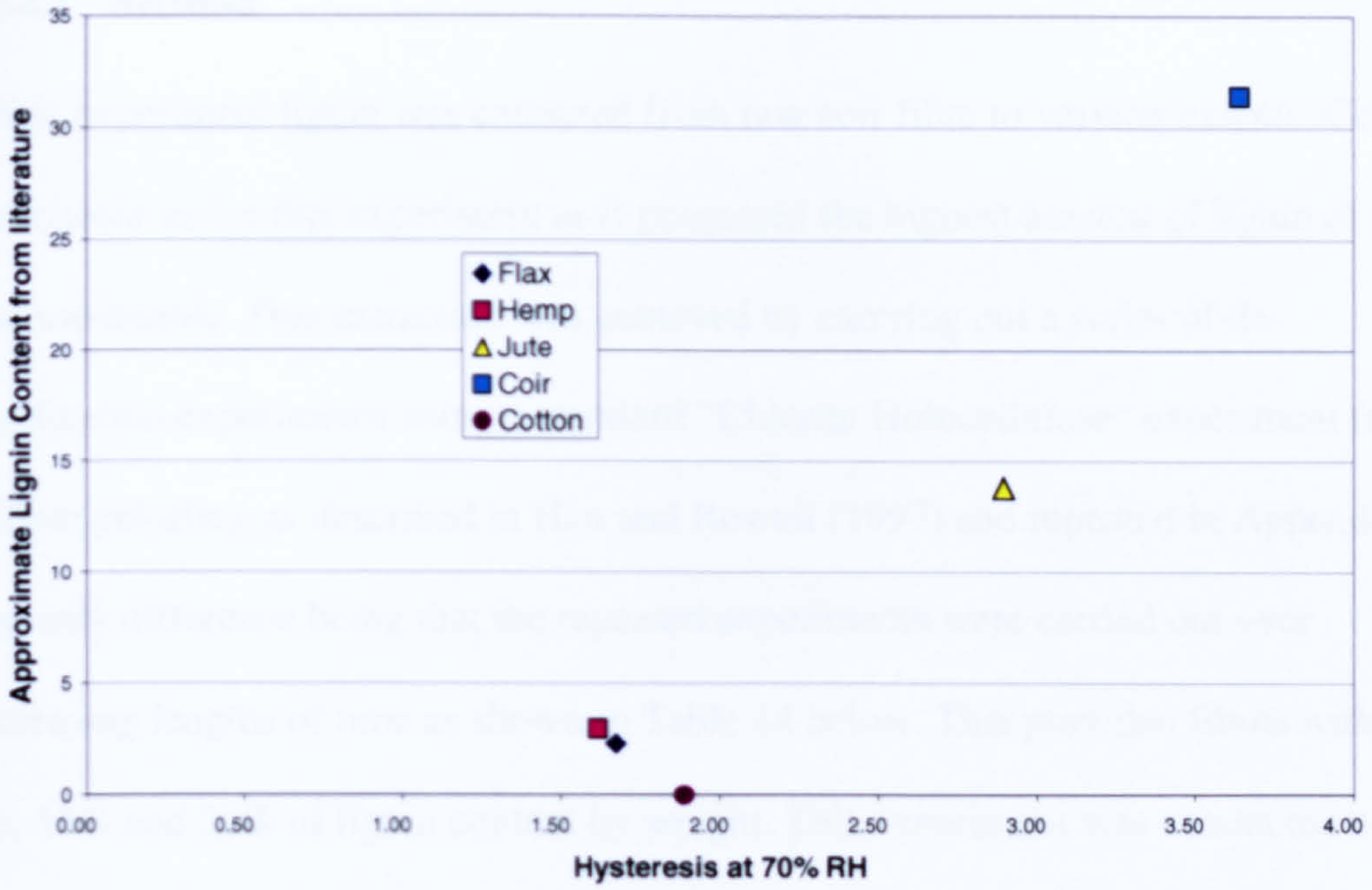


Figure 56 a graph to show the hysteresis exhibited by various natural fibres studied at 70% RH

As it was noted from the literature review that flax, hemp and cotton all possessed low quantities of lignin when compared to jute and especially coir, it was thus thought that a relationship between the quantity of lignin and the amount of hysteresis displayed by a fibre may exist as displayed in Figure 56. A brief further study was devised to test this theory as presented in Experimental 2 below.

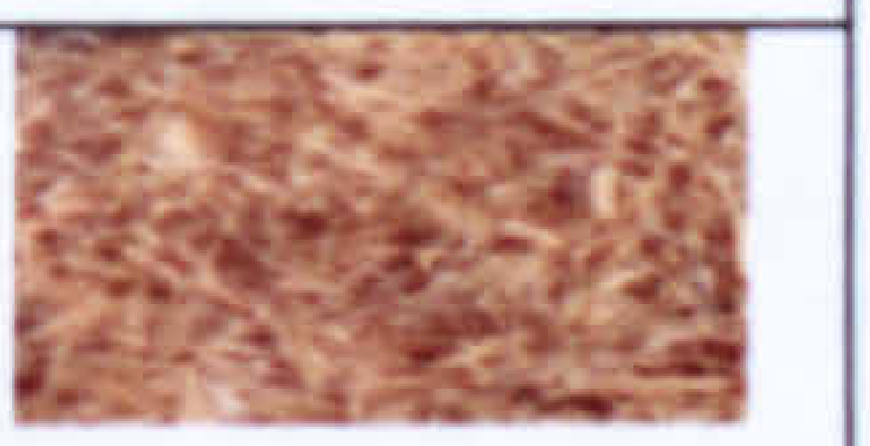
6.3.2 Experimental 2

It was noted from Experimental 1 that natural fibres possessing large quantities of lignin also displayed large sorption hysteresis, as such an experiment was designed to study the affect of lignin on natural fibre sorption characteristics in a more controlled manner.

6.3.2.1 Method

In this experiment lignin was extracted from raw coir fibre to varying extents. Coir was chosen as for this experiment as it possessed the highest amount of lignin of the fibres available. This extraction was achieved by carrying out a series of de-lignification experiments using a standard "Chlorite Holocellulose" experiment (using sodium chlorite), as described in Han and Rowell (1997) and repeated in Appendix V. The only difference being that the repeated experiments were carried out over decreasing lengths of time as shown in Table 14 below. This provided fibres with 0%, 9%, 16% and 26% of lignin content by weight. This experiment was conducted with the assumptions that the initial lignin content of the starting coir fibre was 26% and that the only material removed in these experiments was lignin. The water sorption characteristics of the raw and "bleached" fibres (depicted in Table 14) were then studied using the DVS analyser to provide comparable isotherms at 25°C.

Table 14 the length of "chlorite holocellulose" experiment conducted on coir fibre stating the quantity of lignin remaining and depiction.

Length of delignification procedure	Assumed final lignin content (%)	Picture of sample
5 hr	0	
2 hr	9	
1 hr	16	
0 hr (raw coir)	26	

6.3.2.2 Reduction in data points

In terms of experimental design it was also decided to remove some of the 5% RH increments programmed into the DVS for data collection. In this experimental (between 10% and 80% RH) they were replaced with 10% RH increments, thus speeding up the lengthy data collection period. This decision was made after it was observed that the most notable adsorption and desorption changes in the results produced by various natural fibres occurred outside of this range, *i.e.* in the regions of 0-10% RH and 80-95% RH.

6.3.2.3 Results

The averaged results of two full adsorption/desorption cycles for each lignin content are presented in Figure 57 and Figure 58 below, with a presentation of the effect of this delignification on the hysteresis properties following in Figure 59.

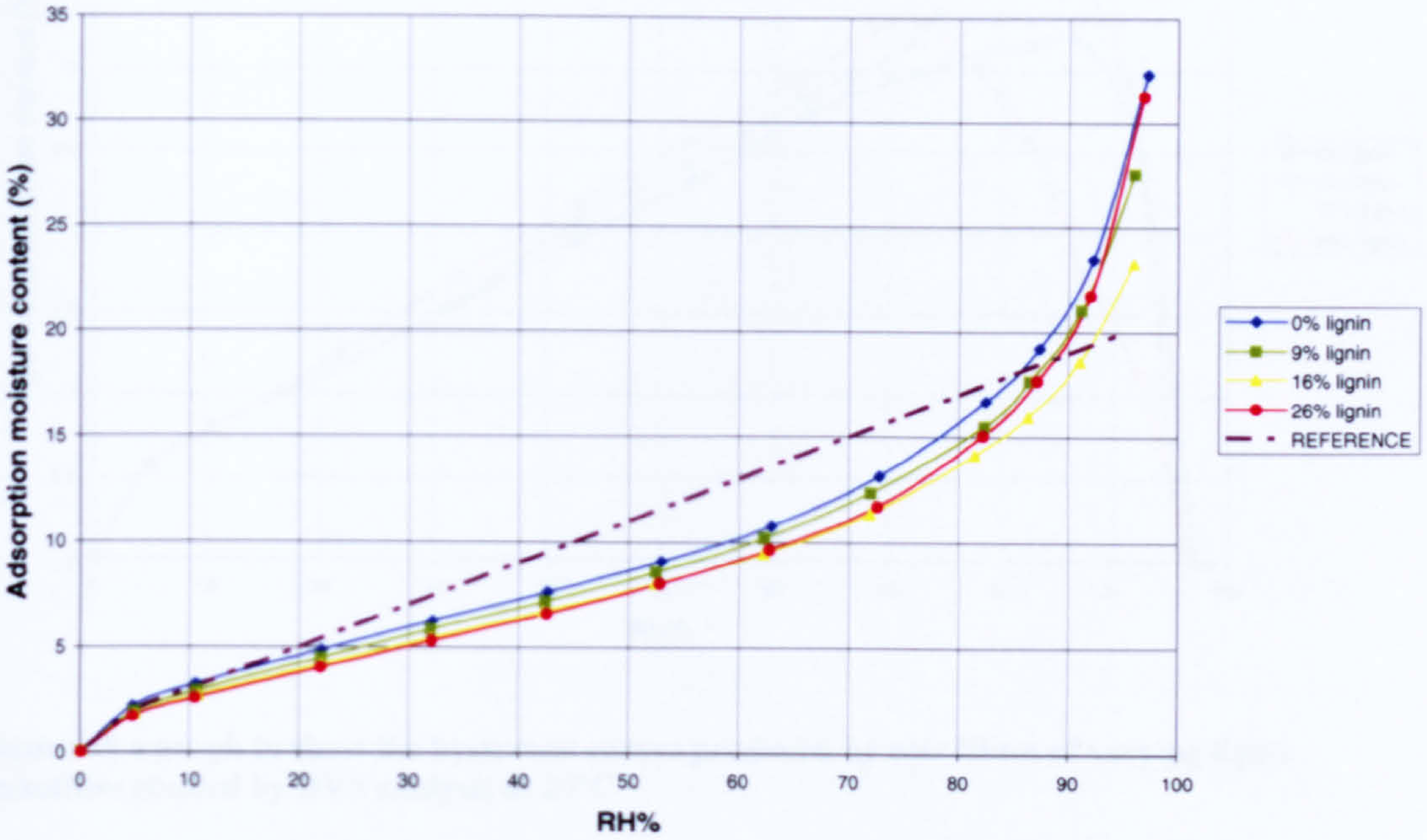


Figure 57 a graph to show the adsorption curves produced by coir fibres of varying lignin quantities studied by DVS analysis at 25°C

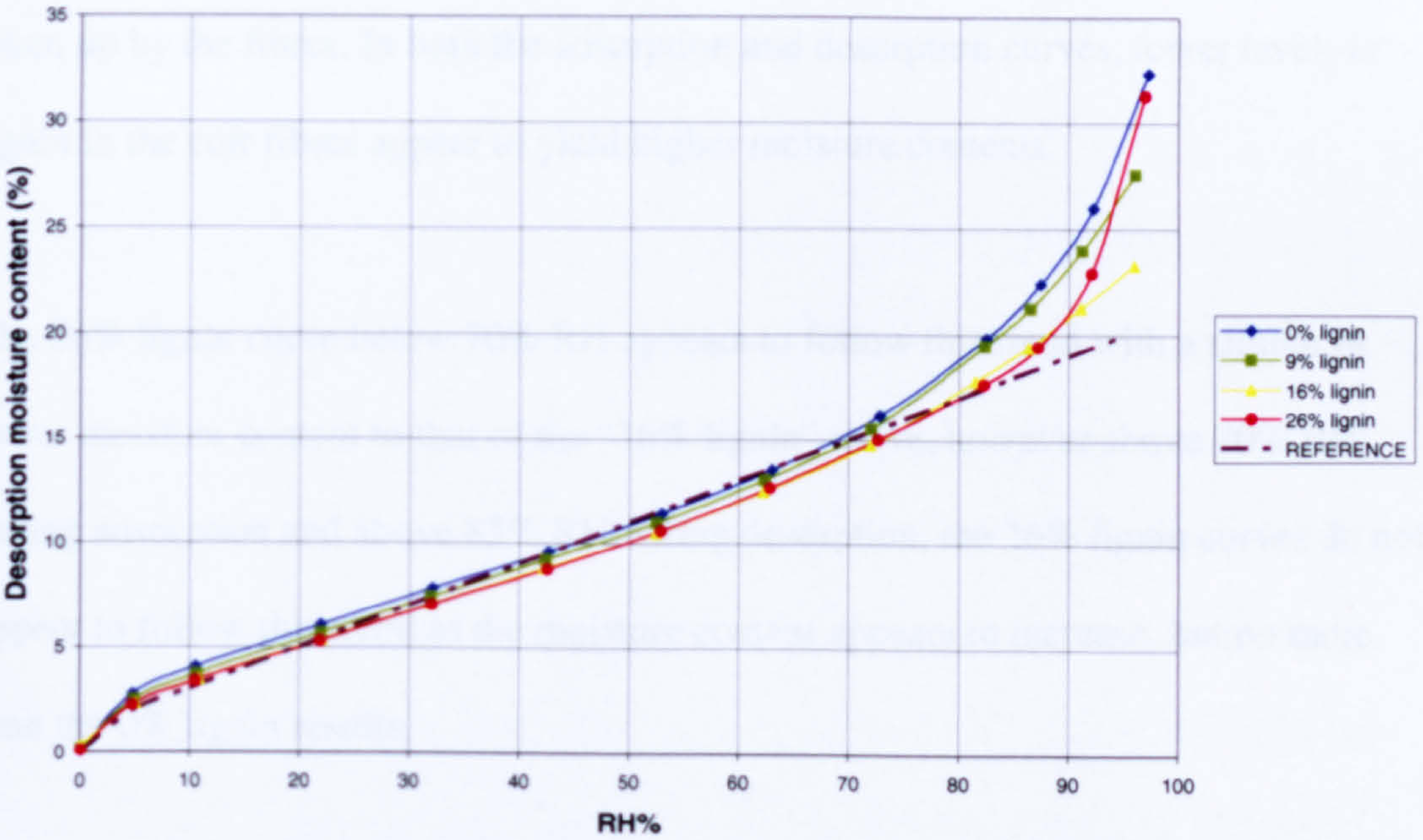


Figure 58 a graph to show the desorption curves produced by coir fibres of varying lignin quantities studied by DVS analysis at 25°C

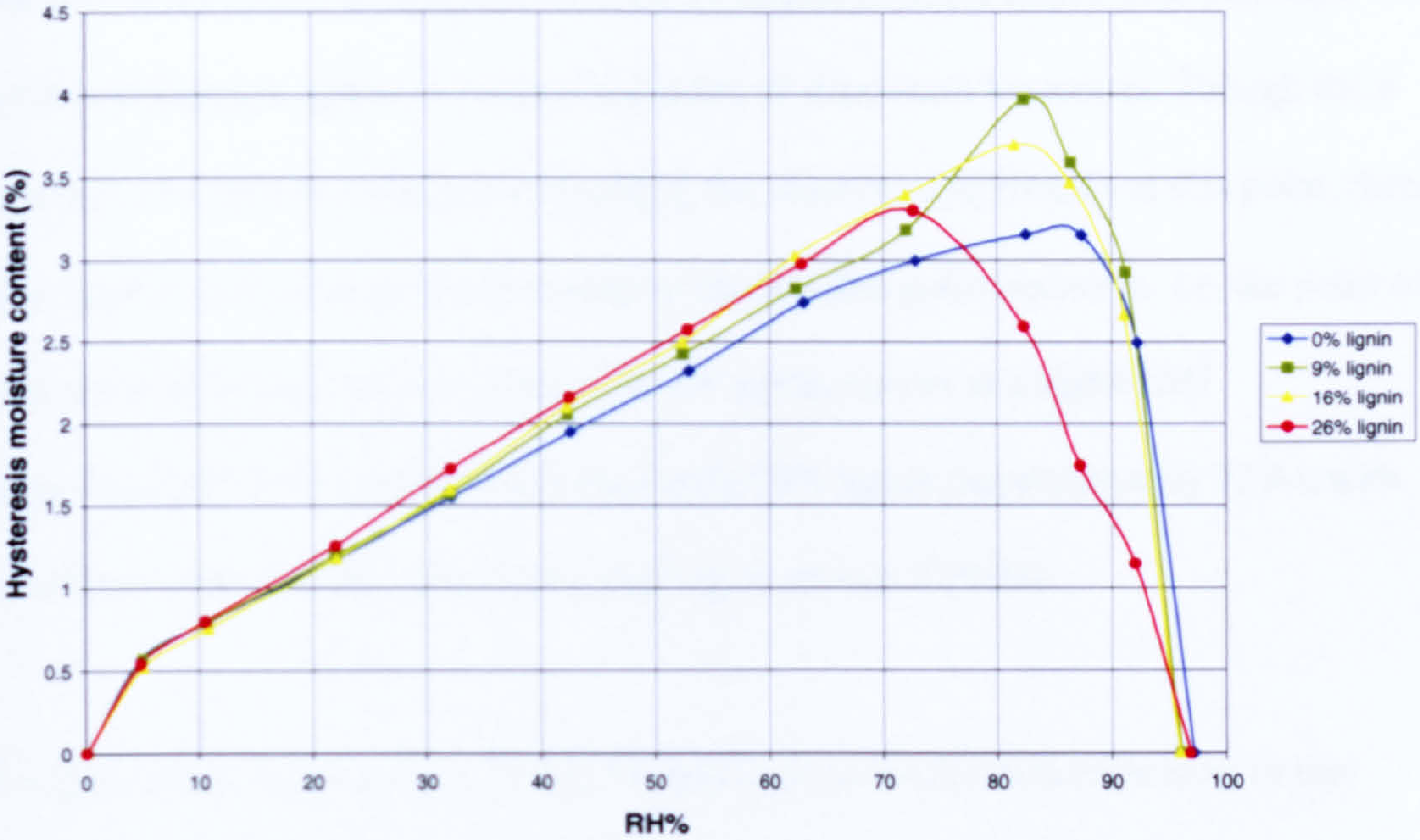


Figure 59 a graph to show the hysteresis curves produced by coir fibres of varying lignin quantities studied by DVS analysis at 25°C

As can be seen in Figure 57 and Figure 58, there appears to be a possible ***negative*** correlation between the amount of lignin in the coir fibre and the quantity of water taken up by the fibres. In both the adsorption and desorption curves, lower levels of lignin in the coir fibres appear to yield higher moisture contents.

The 26% lignin curve below 70% RH appears to follow this trend with a similar or lower moisture content to that of the "16% lignin" curve, however above 70% RH during adsorption and above 85% RH during desorption, the 26% lignin curves do not appear to follow this trend as the moisture content appears to increase, but no more than the 0% lignin results.

From Figure 59 it is noted that there appears to be a possible ***positive*** correlation between lignin percentage and hysteresis moisture content (especially between 30%

and 70% RH). However, greater differences appear to occur above 70% RH. One notable difference appears to regard the point of maximum hysteresis. Though there appears to be no real correlation regarding the amount of hysteresis at this point, there does appear to be a relationship regarding the RH this point occurs at. *i.e.* the point of maximum hysteresis for coir fibres with 0% lignin occurs at a higher RH (approximately 87%) than that of fibres with 26% lignin (approximately 73%), with both fibres with 9% and 16% lignin peaking at around 83%RH.

The decision to remove some of the 5% RH increments for data collection in this study and replace them with 10% RH increments does not appear to have hampered the overall data analysis of the adsorption and desorption curves as very smooth curves where produced. In terms of studying hysteresis however, due to the noted effects of delignification on the point of maximum hysteresis, a data point at 75% RH may have yielded more conclusive data regarding the point of maximum hysteresis attained by the 9% and 16% lignin fibres.

It is not known how the presence or removal of lignin causes the effects noted previously. In terms of the increase in sorption seen with a decrease in the amount of lignin, this is possibly caused by the removal of lignin simply making the fibre structure more open thus exposing more hydroxyl groups or sorption areas to the water vapour. It is also possible that this removal of lignin makes the fibres more flexible and thus its water sorption less restricted especially by the "temporary pores" described by Stamm (1964) that only exist in the presence of water. No further work was carried out in this area to try and ascertain which of these and the many other theories regarding this may be more likely, as this was considered to be tangential to the main aim of study.

6.4 Conclusions and Recommendations

The main conclusions drawn from the two experiments discussed in this chapter are presented here:

- Though there is a possible ***negative*** correlation between the amount of lignin in coir fibre and the moisture content at varied RHs (below 70% RH) the results are inconclusive.

- A reduction in lignin in coir fibres appears to cause an increase in the RH at which the point of maximum hysteresis is observed though further study would be required to verify this.

With regard to the use of the DVS analyser with natural fibres, very smooth adsorption and desorption curves where exhibited for varied natural fibres, indicating that the data produced was of a reliable nature. From this it would appear that samples of natural fibres as small as 4mg can be used satisfactorily in the DVS analyser due to the large quantity of water adsorbed (as compared to synthetic materials studied previously for example).

The reduction in data points (omitted in experimental 2 in order to speed up data collection) appeared to still provide smooth and comparable sorption curves. However, it was noted that for comparisons between hysteresis plots a larger number of data points should be considered.

No further work was carried out to investigate the likely cause of the correlations observed between lignin percentage and moisture sorption however it is suggested that the use of "solute exclusion" (to study the available micro pore sizes) or "deuterium exchange" (to study the quantity of available hydroxyl groups) may provide some useful data for further studies in this area.

7 Heat of Wetting Study

7.1 Introduction

Natural fibres behave very differently to mineral fibres in their ability to adsorb water during changes in RH. Just as removing water from a fibre during drying requires energy, conversely water adsorbed into a fibre releases energy. The energy given off in this process is known as the heat of wetting. The main reasoning behind this section of study was to ascertain the scale of impact of the integral heat of wetting on the life cycle of a given natural fibre insulation product. It is stated in the literature that the differential heat of wetting can be measured by means of calculation (using the Clausius-Clapeyron equation) using data from sorption isotherms that have been collected from experiments conducted at two or more temperatures. As previously described (in Section 5.10 in Chapter 5) a plot of the differential heats of wetting at different moisture contents can then be used by a method of integration to find the integral heat of wetting. It is this integral heat of wetting that represents the energy required (or released) during a given change in moisture content bought about by a change in RH.

As an insulation material is exposed to many RH changes over its lifetime, it is possible that this total energy may be of a magnitude where it may affect the energy usage of a dwelling. If this is found to be the case then the environmental impact of such a material could be affected over its life cycle. As such the aim of the experimental work described in this chapter is to produce data that can be used to calculate the effect of the (integral) heat of wetting on the products' LCA. The DVS analyser described in Chapter 6 was used to perform sorption experiments at different temperatures on a selection of materials in order to validate the methodology. These are Sitka spruce, hemp and flax.

7.1.1 Importance of integral heat of wetting figures

A preliminary calculation was performed to ascertain the possible importance of this area of study. Using differential heat of wetting figures for beech wood (Weichert, 1963, presented in Skaar, 1972) in the absence of such figures for hemp fibre, it was possible to roughly calculate the impact of the integral heat of wetting in an example (2 bedroom) dwelling with a 40m^2 loft as follows, with the assumption that beech wood and hemp fibres will have a similar integral heat of wetting:

Given an example RH change of 30% between a day (30%) and night (60%) in a given loft space, an approximate gain of water of 4% by weight would be expected by a hemp fibre insulation material *i.e.* a change between 4 and 8% mc. Using data from Weichert, (1963, presented in Skaar, 1972) on beech wood as a surrogate for the natural fibres in the insulation, this would release approximately 12 Joules* of energy per gram of water adsorbed (*the method for this calculation is given in the following methodology Section 7.2). 320kgs of insulation would be required to insulate the example loft to the required UK standard. During this 30% flux in RH some 13kg of water will be adsorbed releasing 156,600 Joules (or 43 watt hours) of energy. Given that an average household of this size uses around 6000 watt hours of energy per day this would equate to providing the equivalent of around 0.7% of the household's energy use during a night where this flux in RH was observed in the loft space. In a more efficient home figures of 1000 watt hours of energy per day are reported as such this heat of wetting would equate to over 4% of the home's energy requirement each day this flux occurred.

It is noted however that this energy would be released in all directions and thus only up to half of this could be associated with the dwelling space. It is also noted that during the next theoretical day the same amount of energy would thus be "absorbed" from the house by the insulation as the loft space RH reduces and the material releases moisture. In reality it is noted that it is during the evening and night time that most heating is used and this is also the time when a loft space RH generally increases based on data recorded by Jenkins (Unpub.) which is when this heat energy would be released.

As previously mentioned with regard to other LCA functional units, the natural fibre insulation material studied here is often used as a wall insulator (for sound and thermal insulation purposes) this being the case a far larger amount of material and thus energy released and "absorbed" will be used which could well make a noticeable difference to the energy usage of a given house. The practice of building with hemp/lime is also becoming more popular and the effect studied here could be very useful for moderating the RH/temperature in a dwelling, however without the basic results there is no way of knowing. As such this would appear to be a very interesting if not significant area for research.

The initial assumption that wood and hemp fibres have a similar integral heat of wetting is itself possibly flawed, as for example the ***total*** integral heat of wetting for beech has been shown to be 69.5 J/g whereas for flax (a similar fibre to hemp, though by no means identical) a lower figure of 54.3 J/g has been shown (Dunlap, 1913 and Guthrie, 1949 respectively from Stamm, 1964). There would appear to be a current lack of available data regarding the heat of wetting of hemp fibres that could be used to calculate more accurately the energies involved in the life cycle of the product. *i.e.* data regarding the ***differential*** heat of wetting so that the correct portion of the ***integral*** heat of wetting can be calculated. *i.e.* relevant to the predicted moisture contents found ***in situ***. It was the aim of this experimentation to provide data for such a calculation.

7.2 Methodology

Calculating the differential heat of wetting from sorption isotherms is a well established method in the area of wood science. It is often referred to as the thermodynamic method and an adaptation of a generally accepted method is presented here. A short discussion regarding initial complications with the use of this method in conjunction with data produced by the DVS, is also included in this section in order to explain the final methodology used.

7.2.1 Calculation of the heat of wetting from sorption isotherms

A method of determining the differential heat of wetting using an integrated form of the Clausius-Clapeyron equation was used in this study and was adapted from the thermodynamic method described in Skaar (1972).

As previously mentioned in Chapter 5 the ***integral*** heat of wetting can be calculated if the ***differential*** Heat of wetting (Q_L) is known for a number of moisture sorption points in order to plot the relevant curve. Integration of the resultant curve from zero moisture content to fibre saturation point will find the total area under the graph (shown in yellow here in Figure 60) *i.e.* the ***total*** integral heat of wetting. If many figures for the differential heat of wetting at different moisture contents are known then a portion of the integrated graph can be calculated, *e.g.* the area under the curve between the estimated moisture contents in the example given in the introduction to this chapter.

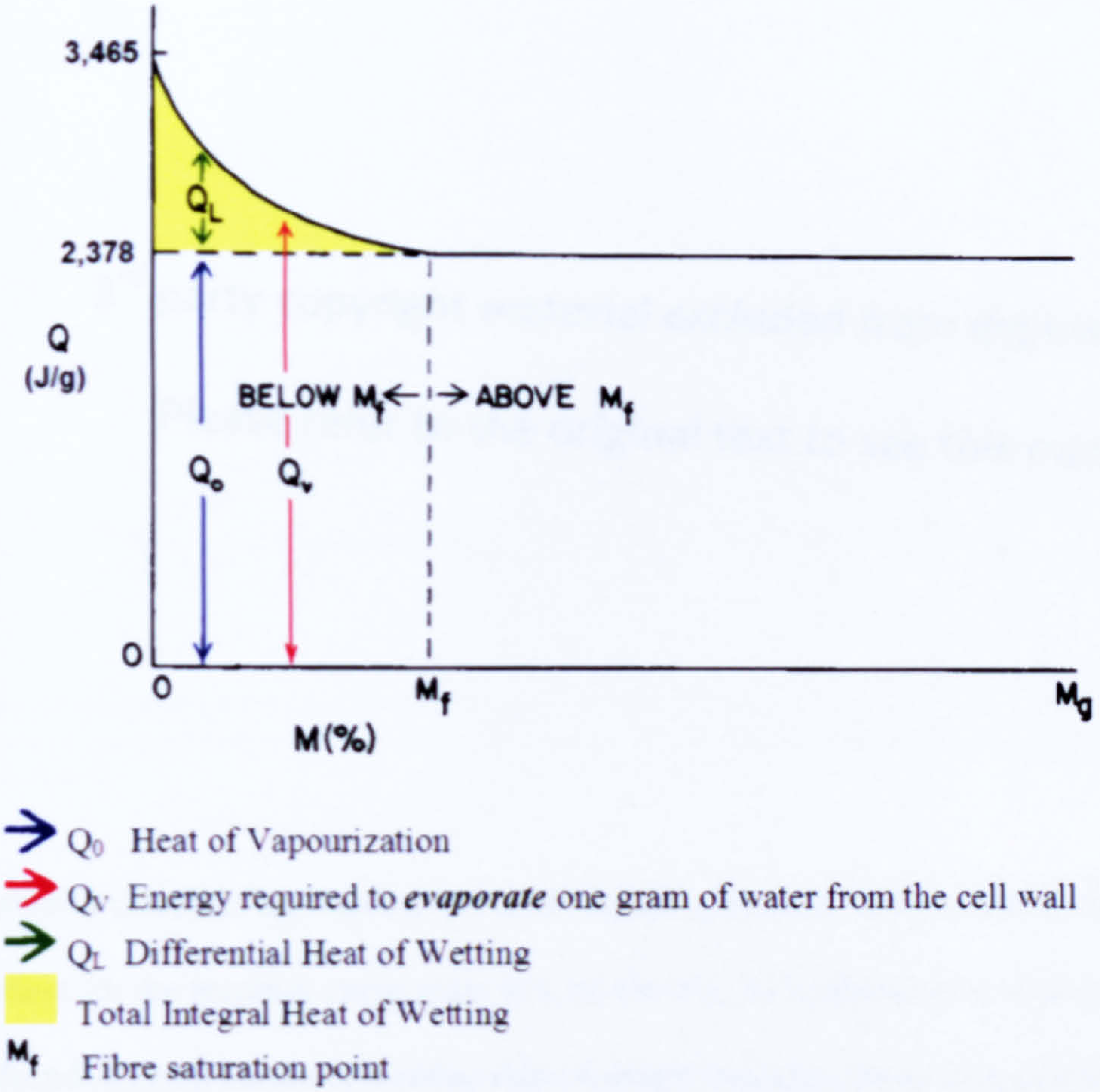


Figure 60 a schematic diagram to show the sorption energy Q (J/g-water) of water in a plant fibre as a function of the moisture content M of the fibre below and above the fibre saturation point Mf. Adapted from Skaar (1972)

It is possible to calculate Q_V using the results from sorption isotherms at two or more temperatures inputted into the ***Clausius-Clapeyron*** equation. As Q_O is known to be 2,378 Joules per gram, the ***differential*** heat of wetting Q_L can thus be calculated. In order to do this the partial vapour pressure *h* (calculated as p/p_0) achieved at a given moisture content (%) at two different temperatures must be known. These can be taken from sorption curves as shown in Figure 61 below.

In order to calculate the required humidity figures precisely from isotherm data, the equation for the sorption curve must first be known. As isotherm data is generally produced at given humidity's rather than moisture contents, these figures were calculated in this study by finding the best fit (6 order) polynomial equation for a plot of moisture content on the X axis, against humidity on the Y axis. This is show here in Figure 62 using the example of data presented in the Wood Handbook (U.S. Forest Products Laboratory, 1974) on Sitka spruce for 21.1 and 82.2°C in order to follow on from the example presented in Skaar (1972) as the data would appear to be identical.

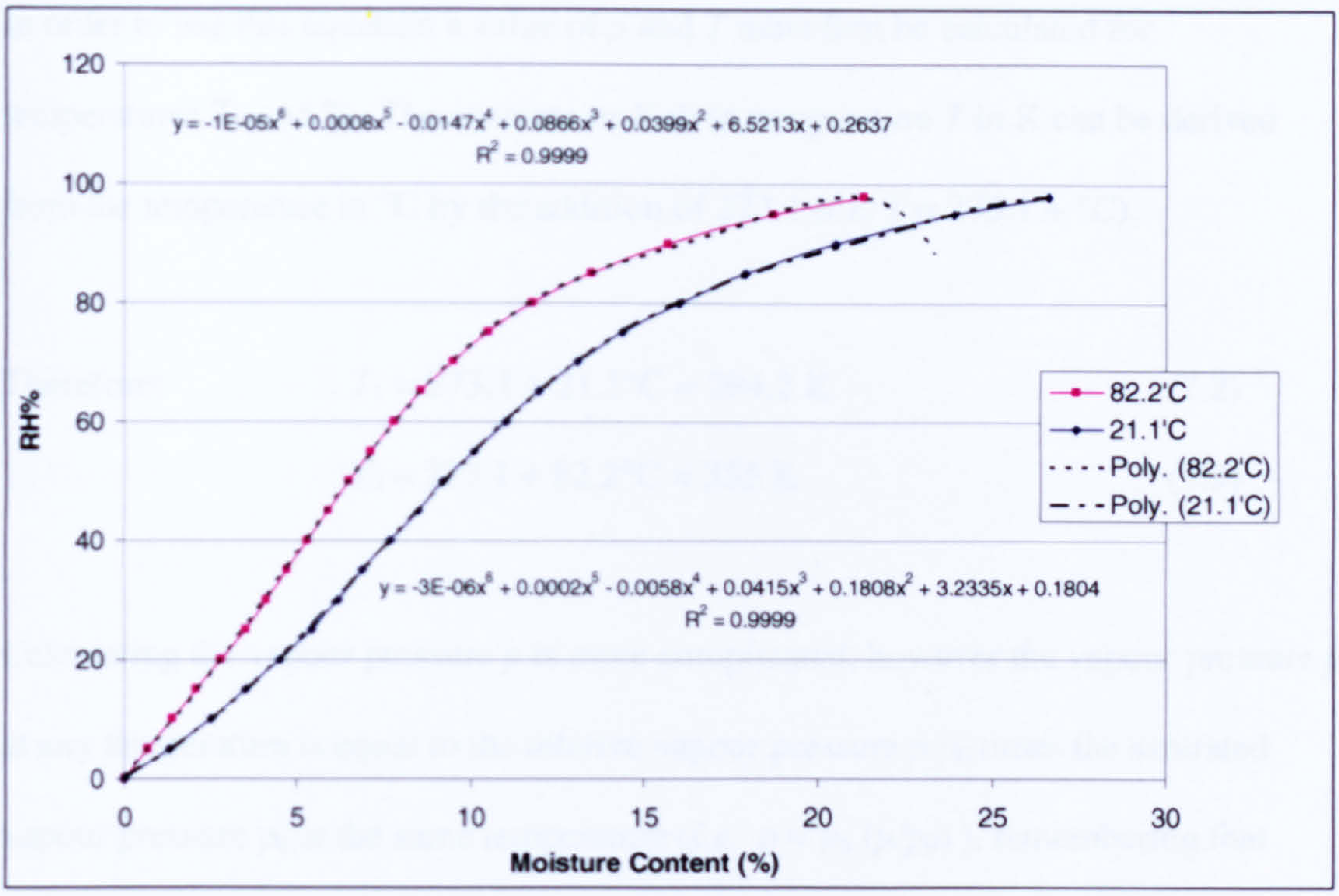


Figure 62 a plot to show the six figure polynomial best fit curves obtained from the Sitka spruce data presented in the Wood Handbook (U.S. Forest Products Laboratory, 1974). Note the very good fit of the curves denoted by the exceptionally high R^2 value obtained

Using the best fit curves produced in the program Excel, accurate RHs (equal to p/p_0 multiplied by 100) can be predicted from the curves at given moisture contents. These values can then be used to solve the following equation which has been adapted from the Clausius-Clapeyron equation (as presented in Skaar, 1972).

$$Q_V = -1.06172 \times (\log p_1 - \log p_2) / (1/T_1) - (1/T_2) \qquad (7.1)$$

Where p is the vapour pressure at a given temperature, T is the temperature in K and Q_V is given in J/g. The original equation presented in Skaar (1972) has been converted here to provide a figure in J/g from the original cal/g by applying the multiplication factor of 4.18 on the original constant of -0.254.

In order to use this equation a value of p and T must first be calculated for temperatures T_1 and T_2. The absolute or Kelvin temperature T in K can be derived from the temperature in °C by the addition of 273.1 (*i.e.* $T = 273.1 + °C$).

Therefore:

$$T_1 = 273.1 + 21.1°C = 294.2 \text{ K} \quad (7.2)$$

$$T_2 = 273.1 + 82.2°C = 355 \text{ K} \quad (7.3)$$

Calculating the vapour pressure p is more complicated, however the vapour pressure p at any temperature is equal to the relative vapour pressure p/p_0 times the saturated vapour pressure p_0 at the same temperature (*i.e.* $p = p_0\ (p/p_0)$), remembering that p/p_0 is equal to the RH divided by 100.

From studies regarding the spacing of water molecules at different temperatures it has been approximated that:

$$\text{Log}\ p_0 = 8.94\text{-}(2260/T) \quad (7.4)$$

Where p_0 (in mm of Hg) is the saturated vapour pressure at a given temperature and T is the temperature in K (Skaar, 1972),

Thus p_0 can be calculated for a given temperature by calculating the reciprocal log of this equation. Referring to the Sitka spruce example the following figures can be calculated:

For p_1

$$\text{Log}\ p_0 = 8.94\text{-}(2260/294.2) \quad (7.5)$$

$$\text{Log}\, p_0 = 1.258 \tag{7.6}$$

$$p_0 = 18.12 \tag{7.7}$$

for a 10% mc the RH was calculated as 54.21 thus giving a p/p_0 value of 0.5421

$$p_1 = p_0\,(p_1/p_0) \tag{7.8}$$

$$p_1 = 18.12 \text{ x } (0.5421) \tag{7.9}$$

Therefore $$p_1 = 9.823 \tag{7.10}$$

For p_2 $$\text{Log}\, p_0 = 8.94\text{-}(2260/355) \tag{7.11}$$

$$\text{Log}\, p_0 = 2.58 \tag{7.12}$$

$$p_0 = 379.47 \tag{7.13}$$

for a 10% mc the RH was calculated as 72.84 thus giving a p/p_0 value of 0.7284

$$p_2 = p_0\,(p_2/p_0) \tag{7.14}$$

$$p_2 = 379.47 \text{ x } (0.7284) \tag{7.15}$$

Therefore $$p_2 = 276.41 \tag{7.16}$$

Using these figures the differential heat of wetting Q_L at 10% mc can be calculated using the previously described adapted form of the Clausius-Clapeyron equation (equation 7.1) to first work out Q_V:

$$Q_V = -1.06172 \text{ x } (\log p_1 - \log p_2) / (1/T_1) - (1/T_2) \tag{7.17}$$

$$Q_{V0.1} = -1.06172 \text{ x } (\log 9.823 - \log 276.41) / (1/294.2) - (1/355) \tag{7.18}$$

$$Q_{V0.1} = -1.06172 \text{ x } (1.449) / (-0.000585) \tag{7.19}$$

$$Q_{V0.1} = -1.06172 \text{ x } (1.449) / (-0.000585) \tag{7.20}$$

$$Q_{V0\,1} = 2629 \text{ J/g} \tag{7.21}$$

Remembering from Figure 60 that $Q_L = Q_V - Q_O$ (Q_O being the heat of vaporisation, known to be 2378 J/g) the differential heat of wetting at a 10% mc for Sitka Spruce (Q_L) is therefore **251 J/g** (*i.e.* 2629 J/g –2378 J/g).

In order to calculate the ***integral*** heat of wetting a plot of a wide range of differential heat of wettings must be plotted and then integrated. Therefore if the ***total*** integral heat of wetting is desired then figures must be calculated from 0% mc to fibre saturation point. This has been done using data in the Wood Handbook (U.S. Forest Products Laboratory, 1974) on Sitka Spruce for 21.1 and 82.2°C. Using calculations in the same manner as previously described the following plot is produced (shown in Figure 63).

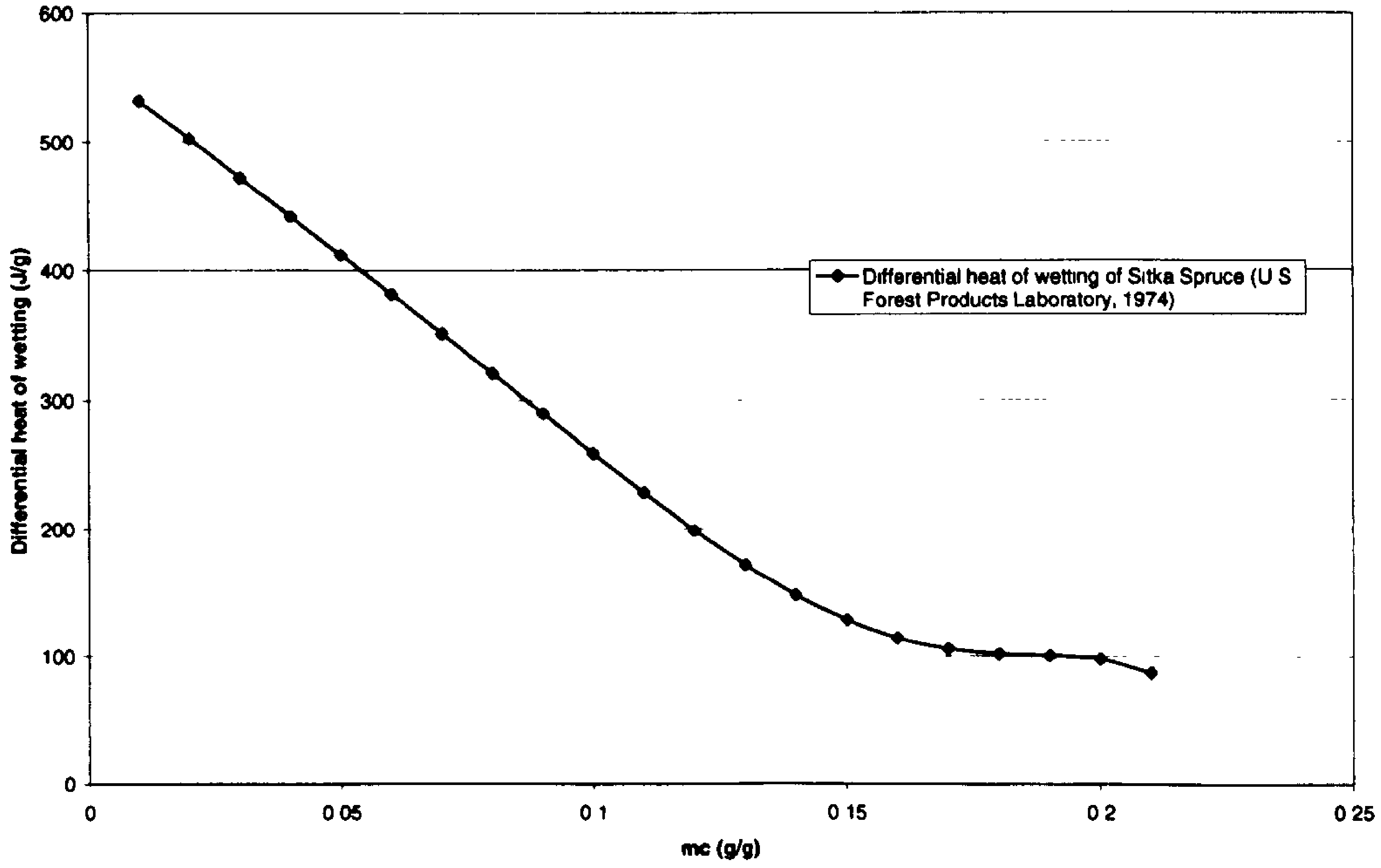


Figure 63 the differential heat of wetting of Sitka Spruce (U.S. Forest Products Laboratory, 1974) as presented between 0.01 and 0.21 g/g mc. Note the near perfect linear relationship displayed by the data below 0.14 g/g mc ($R^2 = 0.9999$ for the line $y = -3031.3X + 562.88$)

By plotting this graph in the program Origin (6.1) the calculus function "integrate" was used to calculate the area under the graph. For the data provided (between 0.01 and 0.21 g/g mc) a figure of **51 J/g** is produced.

This is close to a figure for the ***total*** integral heat of wetting except that the differential heat of wetting figures for 0 g/g mc and fibre saturation point are missing. However as a means of validating the method it would be useful to calculate, as such; a figure for 0 g/g mc is not calculable using the previously explained method due to the logarithms used in the equation, however it can be estimated as 562.88 J/g taken from the linear best fit equation for the near perfect linear section of the presented plot $y = -3031.3X + 562.88$.

Stamm (1934) states that the fibre saturation point of Sitka spruce occurs at 0.32 g/g mc at which the differential heat of wetting should in theory be zero. Extending the graph in both directions using these two extra points and re-integrating the resulting graph gives a figure of **59.4 J/g**, for the total integral heat of wetting of Sitka Spruce. In comparison to other total heat of wetting figures presented in Stamm (1964) this figure would appear to be reasonable figure though possibly a little low as figures for wood samples of other species appear to vary between 62 and 84 J/g.

7.2.2 Example using data for beech wood

The example using data on beech wood as a surrogate presented in the introduction to this chapter, was calculated in a similar fashion but was approximated as the area between 4% and 8% (0.04 and 0.08 g/g) mc using the differential heats of wetting figures from Weichert (1963, presented in Skaar, 1972) as presented in Figure 64.

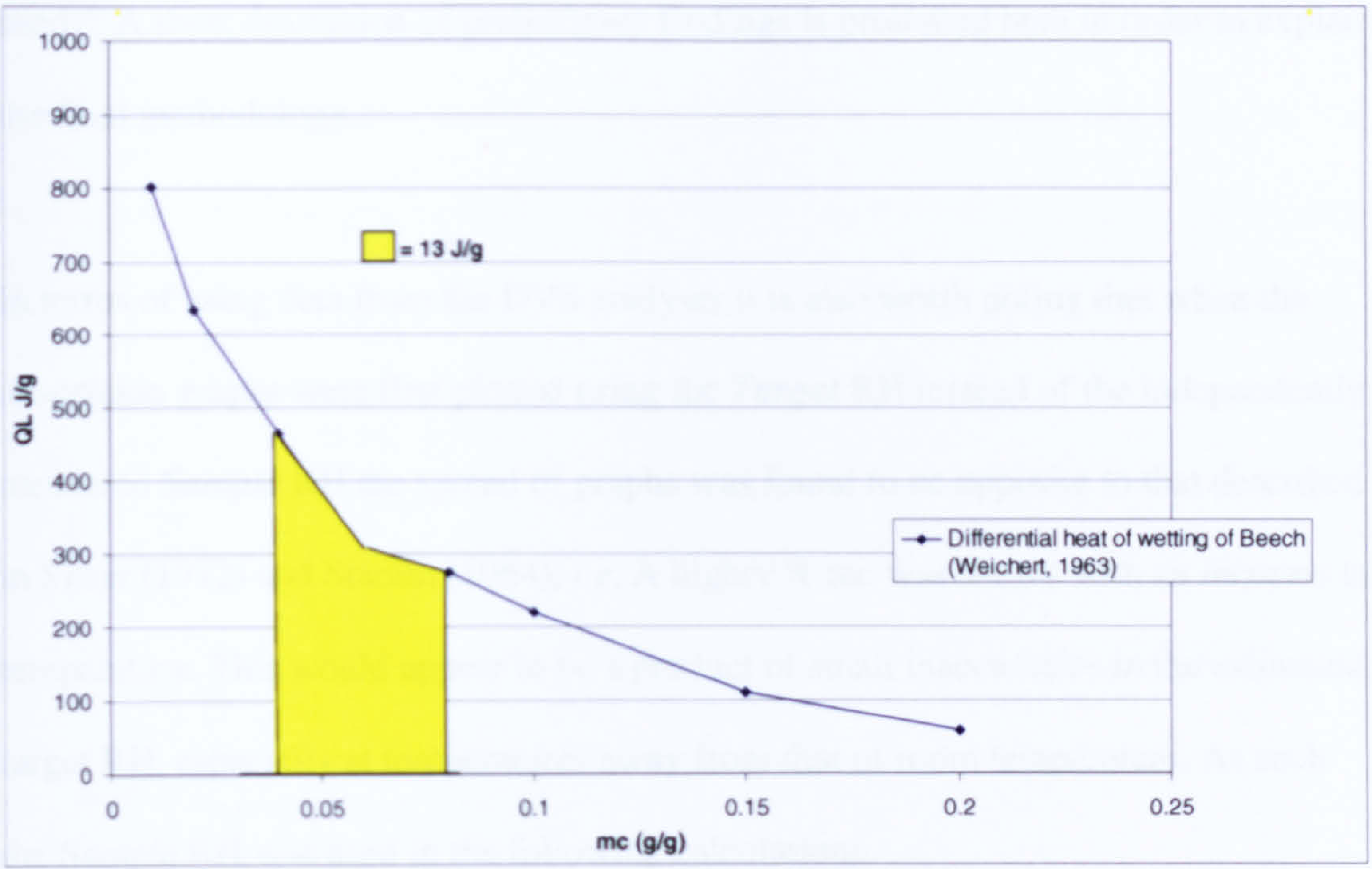


Figure 64 to show the differential heat of wetting (QL) shown by Weichert (1963, presented in Skaar, 1972) and the approximate integral heat of wetting value of 13 J/g between the values of 0.04 and 0.08 mc (g/g).

The value of 13 J/g taken from Figure 64 was used in the original example shown in the introduction to this chapter.

As an extra note regarding the validity of this method, extending the graph in the same manner as described previously with the Sitka Spruce data gives a total integral heat of wetting of 61 J/g which is again a reasonable figure, though slightly lower than that quoted by Dunlap (1913, presented in Stamm, 1964) of 69 J/g.

7.3 Use of DVS data with the thermodynamic method

During initial experiments with varied samples at different temperatures using the previously described method a major question arose: "which isotherms should be used?" A short discussion of preliminary findings is presented here in order to explain the final methodology.

In terms of using data from the DVS analyser it is also worth noting that when the adsorption graphs were first plotted using the ***Target*** RH instead of the independently measured ***Sample*** RH the spread of graphs was found to be opposite to that described in Skaar (1972) and Stamm (1964), *i.e.* A higher % mc was shown with an increase in temperature. This would appear to be a product of small inaccuracies in the estimated target RH, especially at temperatures away from that of room temperature. As such the Sample RH was used in the following calculations.

7.3.1 Which isotherms should be used?

It was initially thought that the differential heats of wetting could be calculated by using the ***ad***sorption curves at different temperatures produced by the DVS analyser, due to assurance from the DVS manufacturer Surface Measurement Systems, that this was possible. It was believed that the ***de***sorption curves should not be used as they would in effect "start" from different points, referring to the differences found between the highest ***ad***sorption points (near fibre saturation point) of samples prior to the "descent" back through the selected RHs in a full sorption cycle experiment. In the unpublished document of DVS Application note 19 (Burnett *et al.*, Unpub.) a method very similar to that described by Skaar (1972) is presented, *i.e.* which uses the Clausius-Clapeyron equation and data from two ***ad***sorption curves of differing temperature.

Preliminary studies with the DVS showed that it was not possible to calculate the differential heat of wetting in this way, as there was no discernable difference shown between ***ad***sorption curves of various materials at different temperatures. For example the three different curves produced by flax fibres at different temperatures shown in Figure 65.

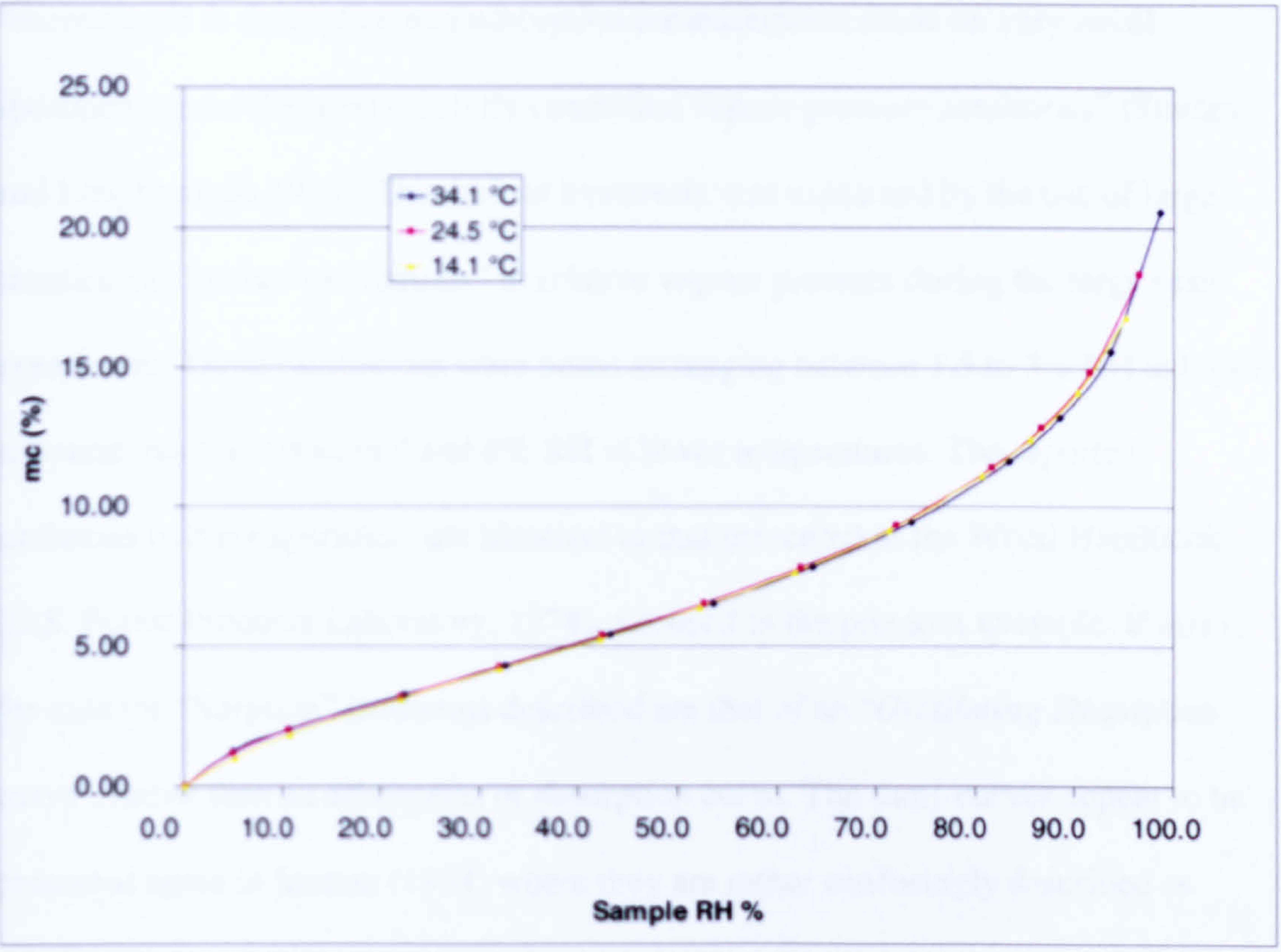


Figure 65 adsorption curves produces by flax fibre samples at different temperatures produced using the DVS analyser

As can be seen from Figure 65 there is no significant difference between the different temperature curves, thus resulting in (both differential and integral) heat of wetting calculations for the sample to be nearly zero. Initially it was thought that flax must simply have a very low heat of wetting, but this relationship was found for a number of fibre types such as hemp, jute and in particular Sitka spruce where a measurable difference was expected bearing in mind the data from the wood handbook (U.S. Forest Products Laboratory, 1974) used in the previous example.

One of the first uses of the Clausius-Clapeyron equation for wood is presented by Stamm and Loughbrough (1934). In this paper the use of "large" (100-125g) samples of Sitka Spruce was thought to have eliminated the hysteresis phenomenon that is "encountered in desorption and adsorption measurements made on very small specimens under the most carefully controlled vapour pressure conditions" (Stamm and Loughbrough 1934). This lack of hysteresis was explained by the use of large samples and by the "oscillations" in relative vapour pressure during the large scale experiment. These oscillations were noted as ranging between 1.5 to 3% RH at higher temperatures and between 4 and 8% RH at lower temperatures. The reported isotherms in this experiment are identical to that presented in the Wood Handbook (U.S. Forest Products Laboratory, 1974), *i.e.* used in the previous example. If this is the case the "Sorption" isotherms described are that of an "***Oscillating De***sorption curve", rather than an ***ad***sorption or ***de***sorption curve. The same curves appear to be presented again in Stamm (1964) where they are rather confusingly described as simply "***De***sorption curves".

If this is the case then it would appear that "oscillating desorption curves" are required for this type of calculation. This however is not possible to perform with the DVS analyser (or with such small samples), however it was thought that an estimate for this would suffice. A good approximation of an oscillating desorption curve is obtained by an average of the data produced by the adsorption and desorption curves at given temperatures to represent a single, non-hysteresis exhibiting curve. It was also considered that the *de*sorption curves alone may provide an accurate answer due to the differences exhibited between the large scale experiment of Stamm (1934) and the very small samples used in the DVS analyser as it is not known whether they are comparable or not. What was apparent however from both this preliminary work and the work of Stamm (1934) was that the ***ad***sorption curves should not be used.

As such calculations using both an "***average*** sorption curve" and the ***de***sorption curve produced by the DVS analyser, were performed and the results are displayed in the following section.

7.4 Results and Discussion

7.4.1 Verification experiment using Sitka spruce.

In order to validate the test, samples of Sitka spruce were first studied with this method in order to see if the differential and integral heat of wetting figures calculated using results from DVS experiments, were similar to that reported in the Wood Handbook (U.S. Forest Products Laboratory, 1974), in the example presented in the previous methodology section. Calculations using both an ***average*** sorption curve (Figure 66) and the ***de***sorption curve (Figure 67) produced by the DVS analyser, are presented here.

By plotting this graph shown in Figure 66 in the program Origin (6.1) the calculus function "integrate" was used to calculate the area under the graph. For the data provided (between 0.01 and 0.21 g/g mc) a figure of 35.8 J/g was produced for the integral heat of wetting for the ***averaged*** sorption plots for Sitka Spruce using DVS isotherms.

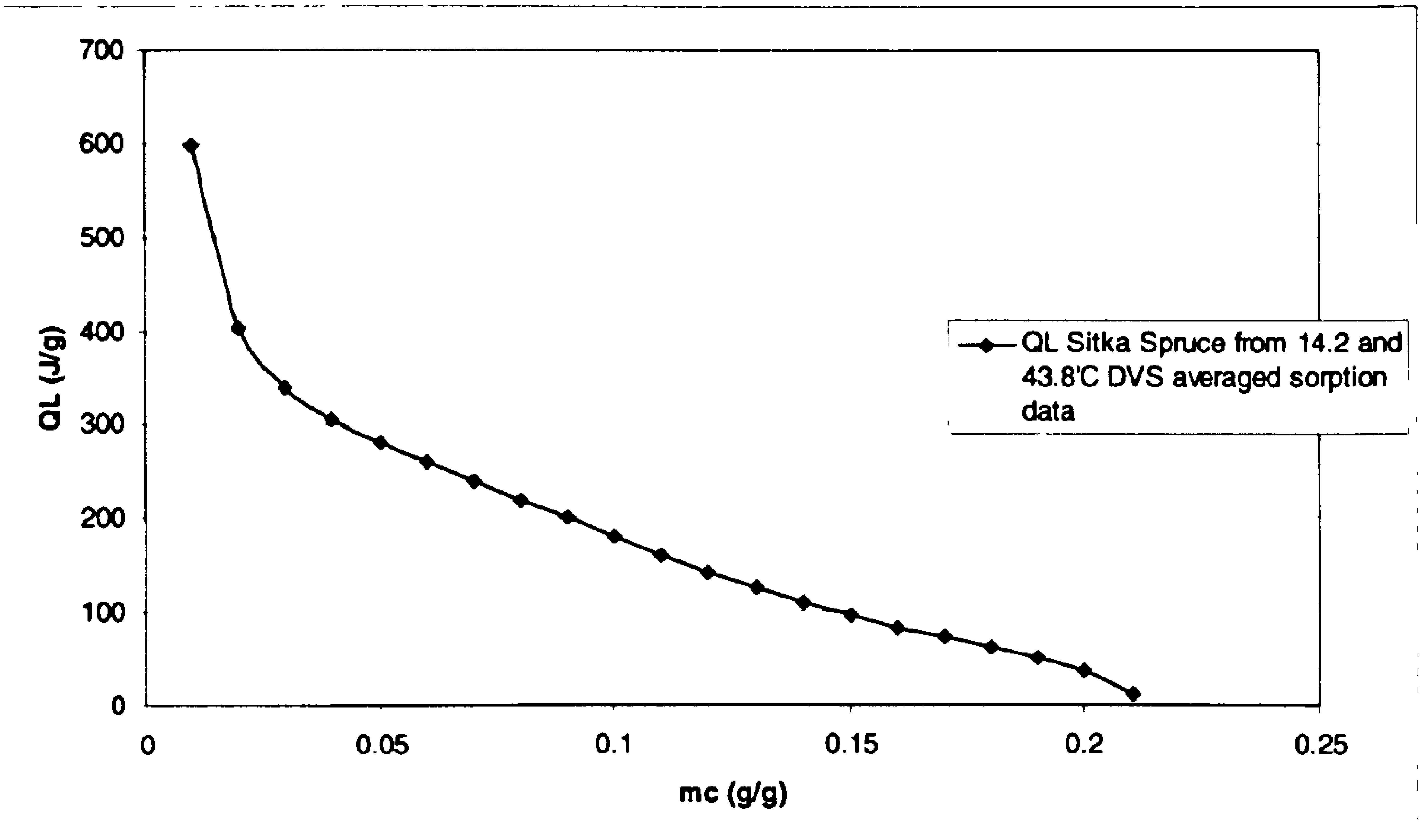


Figure 66 a graph to show the Differential heats of wetting calculated from averaged sorption plots for Sitka Spruce using DVS isotherms

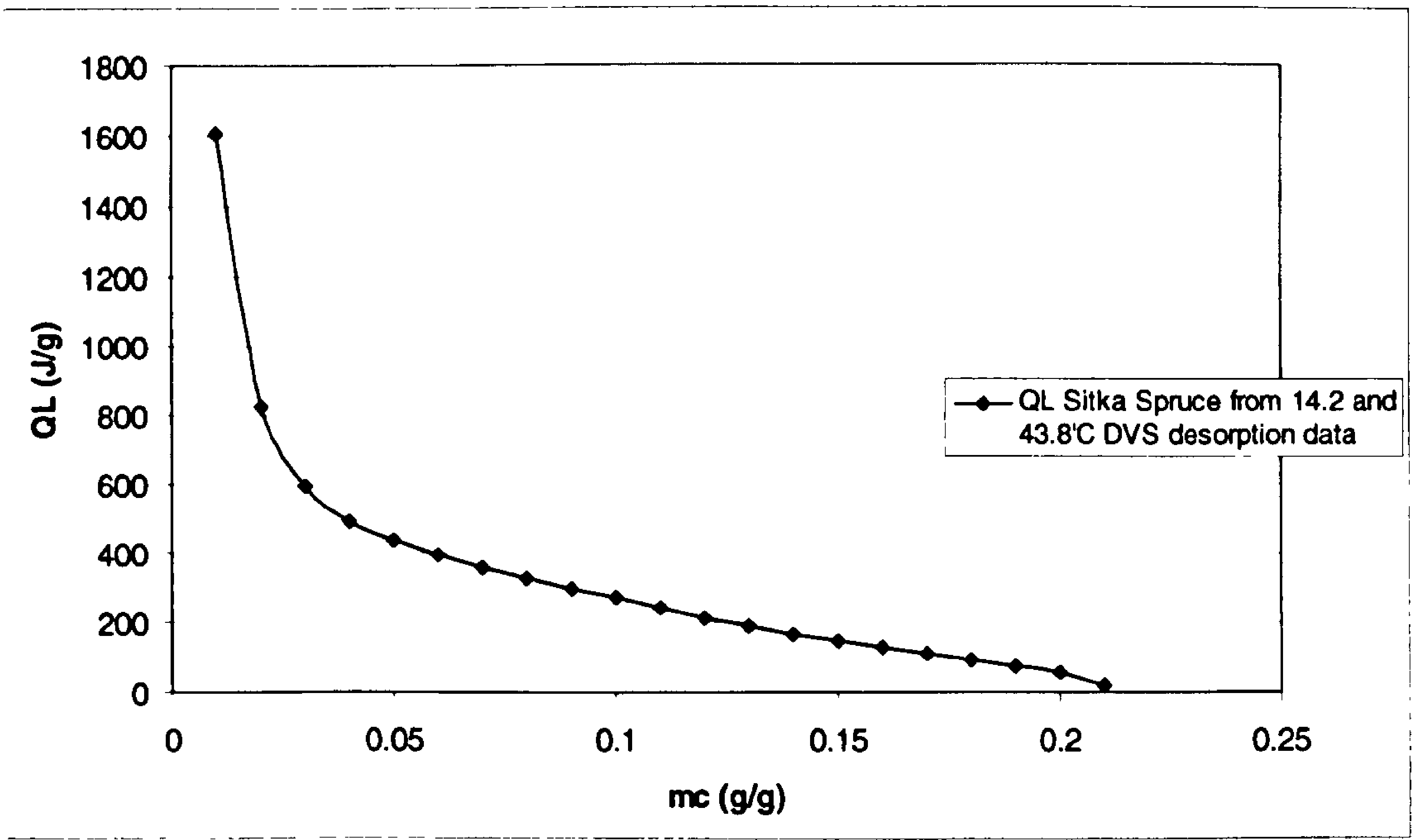


Figure 67 a graph to show the Differential heats of wetting calculated from desorption plots for Sitka spruce using DVS isotherms. Note the different scale used in comparison with Figure 66

Using the same method the graph shown in Figure 67 (also between 0.01 and 0.21 g/g mc) produced a figure of 61.2 J/g for the integral heat of wetting for the ***de***sorption plots for Sitka spruce using DVS isotherms.

If a comparison is made between the two sets of data (average sorption and desorption) used here and the data given in the Wood Handbook (U.S. Forest Products Laboratory, 1974), then it would appear that using the ***de***sorption curves produced a more comparable result, *i.e.* an integral heat of wetting figure closer to 50 J/g produced by the Wood Handbook data between 0.01 and 0.21 g/g mc. Another similarity is the linear relationship shown by (a portion of) the desorption plot. While both sets of the DVS data show a portion of the graph produced to be linear (between the 0.06 and 0.14 g/g mc), it is the ***de***sorption best fit line that is notably similar, that is $y = -2868.5x + 560.22$ ($R^2 = 0.9928$) for the DVS desorption data compared to $y = -3031.3X + 562.88$ for the Wood Handbook data. This may indeed be a coincidence but similarities are nonetheless striking, especially for the point of intercept.

Given these similarities, some uncertainty is raised over the area the below 0.06 g/g mc, as the differential heat of wetting calculated from the DVS data increases rapidly with a decrease in mc whereas the data presented in the Wood Handbook continues linearly. It is simply not known which of the data sets is closer to being "correct" for this area but in terms of the aim of this study it is not thought to be problematic as such low moisture contents are rarely encountered *in situ*. This is also true of very high moisture contents (nearing fibre saturation point).

7.4.2 Integral heat of wetting of hemp fibre

Having established that using the thermodynamic method with data from desorption curves produced by means of DVS analysis give comparable results to other data sets, at least for a certain range of moisture contents, DVS data for hemp fibres was then analysed in the same way. The results are presented below in Figure 68.

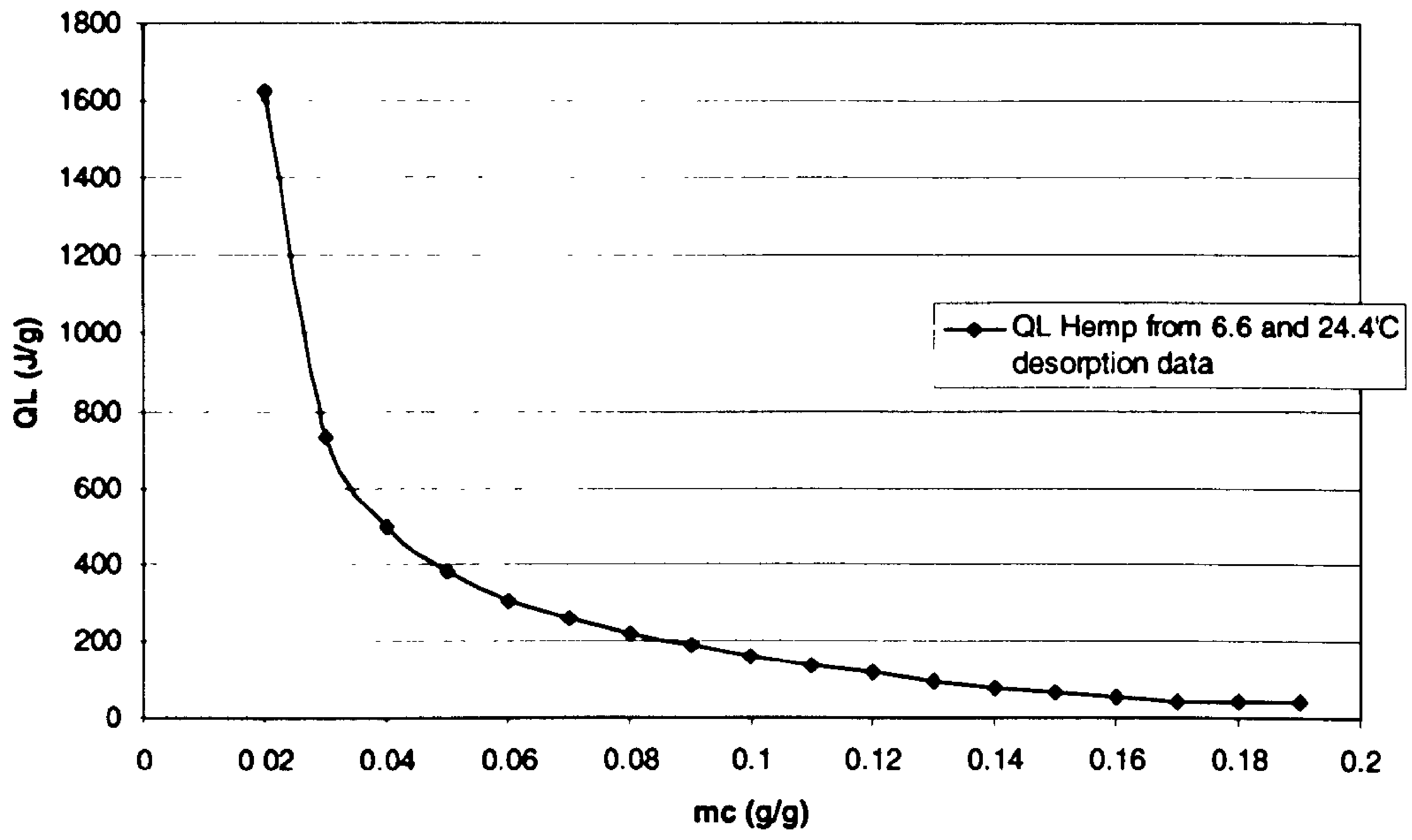


Figure 68 a graph to show the Differential heats of wetting calculated from desorption plots for hemp using DVS isotherms.

By plotting this graph shown in Figure 68 in the program Origin 6.1 the calculus function "integrate" was used to calculate the area under the graph. For the data provided a figure of 41.6 J/g is produced for the integral heat of wetting between 0.02 and 0.19 g/g mc for hemp fibres.

From this data it was possible to re-calculate the initial introductory *in situ* example, where the fluctuation between 30 – 60% RH caused a change in moisture content between 4 and 8%. The result is shown below in Figure 69.

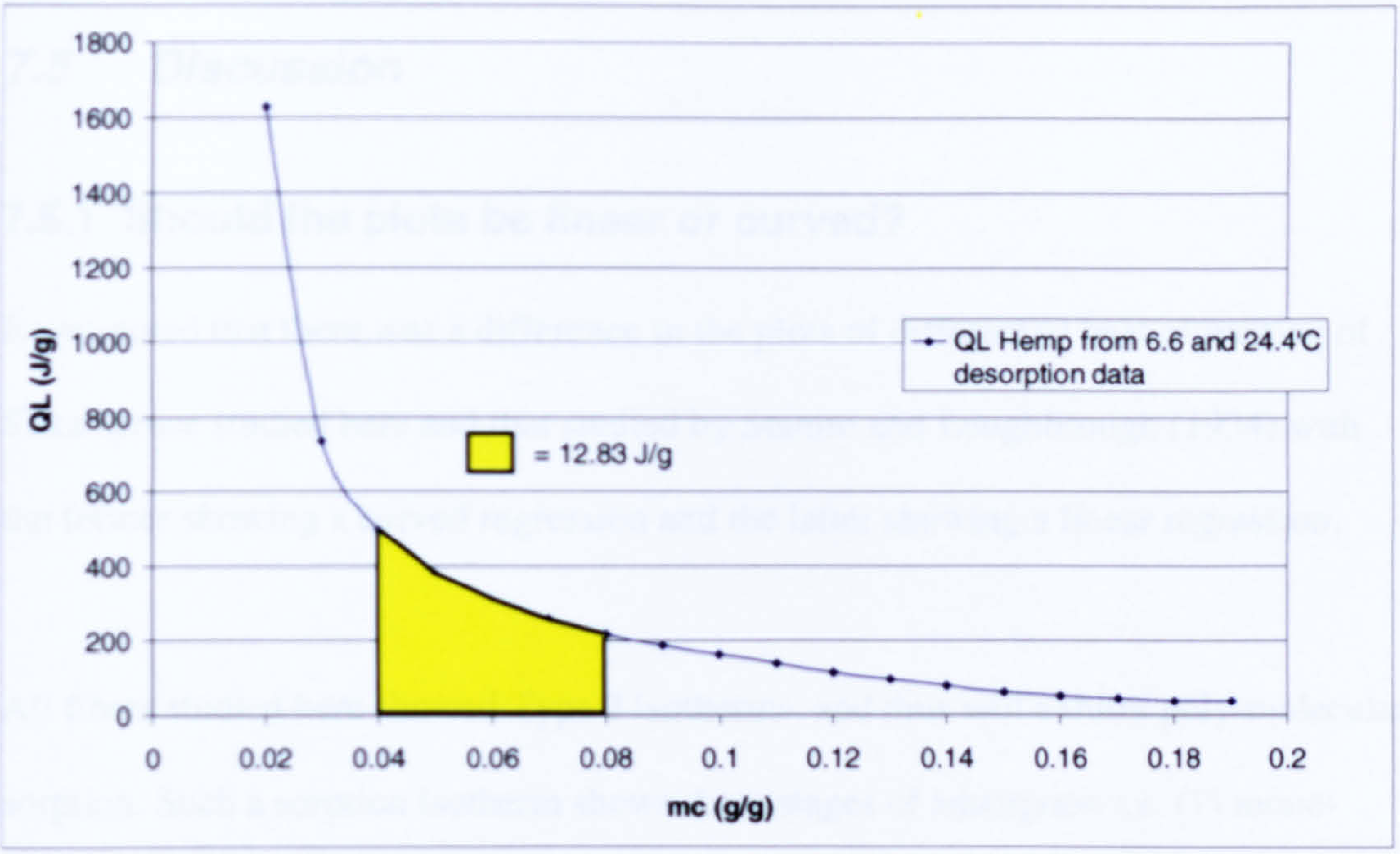


Figure 69 a graph to show the integral heat of wetting calculated from desorption plots for hemp using DVS isotherms between the value of 0.04 and 0.08 g/g mc

As can be seen from Figure 69 (calculated in Origin 6.1) a figure of 12.83 J/g is produced for the integral heat of wetting between 0.04 and 0.08 g/g mc for hemp fibres. This figure is practically identical to the original figure (*i.e.* 13 J/g) calculated using surrogate data on beech, from Weichert (1963), as presented in Skaar, (1972). As such the initial estimate requires no correction.

7.5 Discussion

7.5.1 Should the plots be linear or curved?

It was noted that there was a difference in the plots of differential heat of wetting of Sitka spruce studied here and that studied by Stamm and Loughbrough (1934) with the former showing a curved regression and the latter showing a linear regression.

All fibres studied here showed Type 2 isotherms, and thus will exhibit poly-molecular sorption. Such a sorption isotherm shows three stages of adsorption *i.e.* (1) mono-molecular sorption, (2) poly-molecular sorption and (3) capillary sorption. It may be expected that there are three components of differential heat of wetting corresponding to this, due to the difference in levels of potential energy between the different mechanisms of adsorption. However it is not known whether for example a change from mono to poly-molecular adsorption will result in a change in the ***type*** of differential heat of wetting plot produced, *i.e.* from a curved to a linear regression. It is not possible to say whether the first part of the plots produced here are wrong or not. It would however appear that they are possibly inaccurate at very low moisture contents, for example as shown by an estimation for the differential heats of wetting for flax shown in Figure 70.

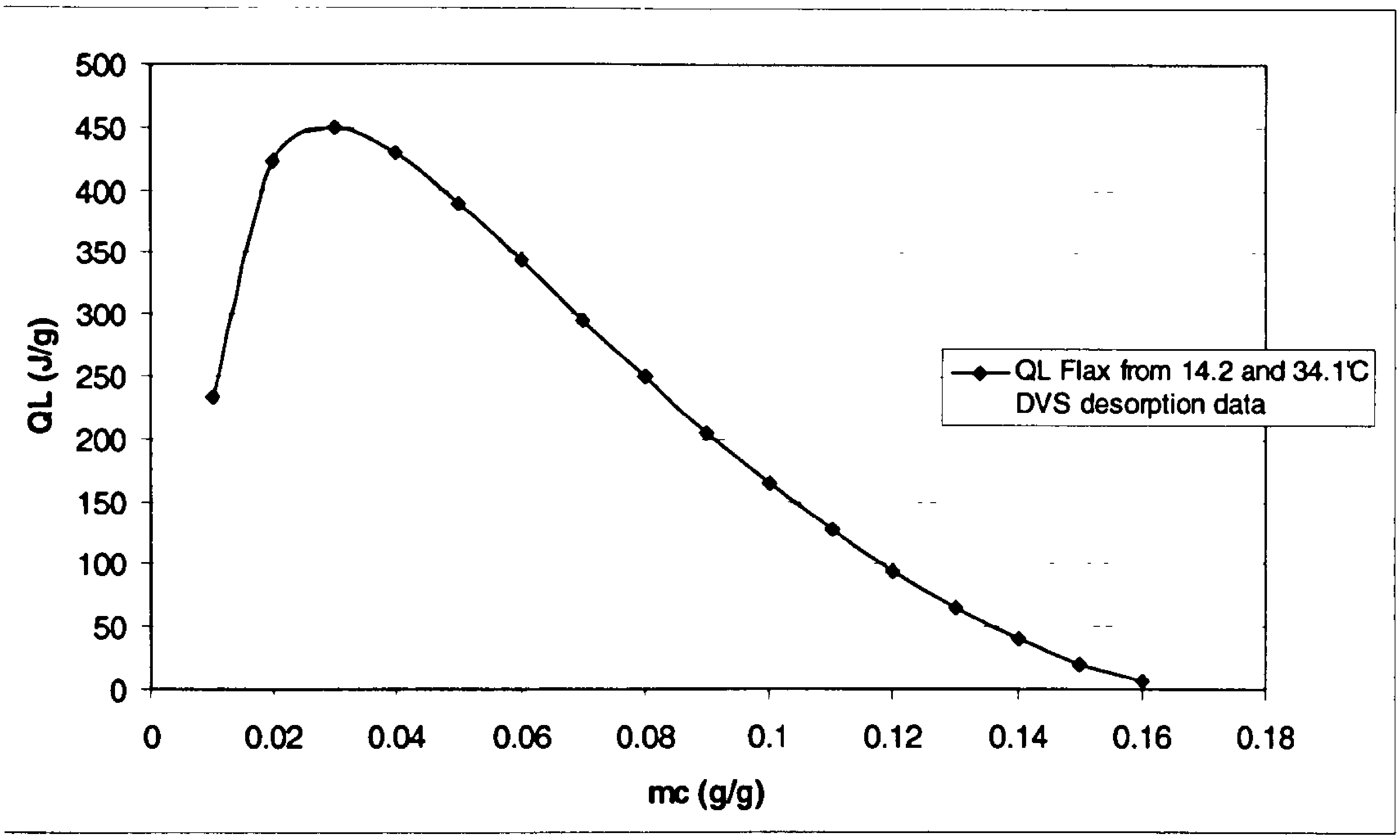


Figure 70 a graph to show the Differential heats of wetting calculated from desorption plots for flax using DVS isotherms. Note the decrease in QL with a decrease in mc below 0.03 g/g mc

The initial increase in Q_L with an increase in mc below 0.03 g/g mc observed in Figure 70 is very unlikely to occur given that a satisfaction of all monolayer sites is likely to cause a drop in the potential energy of the system rather than an increase as shown here by an increase in the differential heat of wetting. As such a question is raised over the limits of accuracy regarding this method.

7.5.2 Limits of accuracy

As shown by the anomalous behaviour of the differential heat of wetting for low moisture contents for flax hemp and Sitka spruce samples, there is possibly a limit to the accuracy of this system below around 0.05 g/g mc. In this area it is noted that the closer to 0 g/g mc during desorption, the DVS system will be closer to the limits of the microbalance accuracy as it will be measuring smaller and smaller amounts of weight loss. It is also noted that the ***effect*** of any background "noise" or any "drift" from the balance will also be greater at this point.

The work of Stamm and Loughbrough (1934) reported the use of much larger samples and could be more accurate at these low mc levels. This being the case it may be that the linear relationship observed in the "mid-range" portion of the graphs could be expected to extend back to the point of zero moisture content. Without comparing the data to other total integral heat of wetting figures (perhaps produced by Calorimetric methods) for the same fibre samples as studied here, this matter cannot be resolved.

This lower limit of accuracy was not seen as a problem in terms of this particular study, as only *in situ* moisture contents were required, however, in terms of validating the test with comparisons against established total integral heats of wetting figures it is problematic.

It is also noted that at high moisture contents the two original DVS ***desorption*** curves (at differing temperatures) for each fibre used for these calculations, will in effect "start" at similar, but slightly different moisture contents. This is due to the difference observed between the "target" and the "sample" RH, so in general at higher temperatures a higher RH and thus moisture content closer to fibre saturation point was achieved. This was thought to only cause inaccuracy at very high RHs *i.e.* over 90-95% as once the next step of decrease in RH (e.g. 80%) is achieved then the readings should be comparable. This was also noted to be an area where the six figure polynomial best fit line, used to predict expected vapour pressure figures for given moisture contents, were inaccurate. Again however, this upper limit of accuracy above 90% RH (or in the case of hemp 16 g/g mc) is not seen a problem as this is outside of the *in situ* moisture contents required by this study.

To summarise, the areas of most likely inaccuracies for the example of hemp has been given in Figure 71 below, which shows the region (B) least likely to contain inaccuracies.

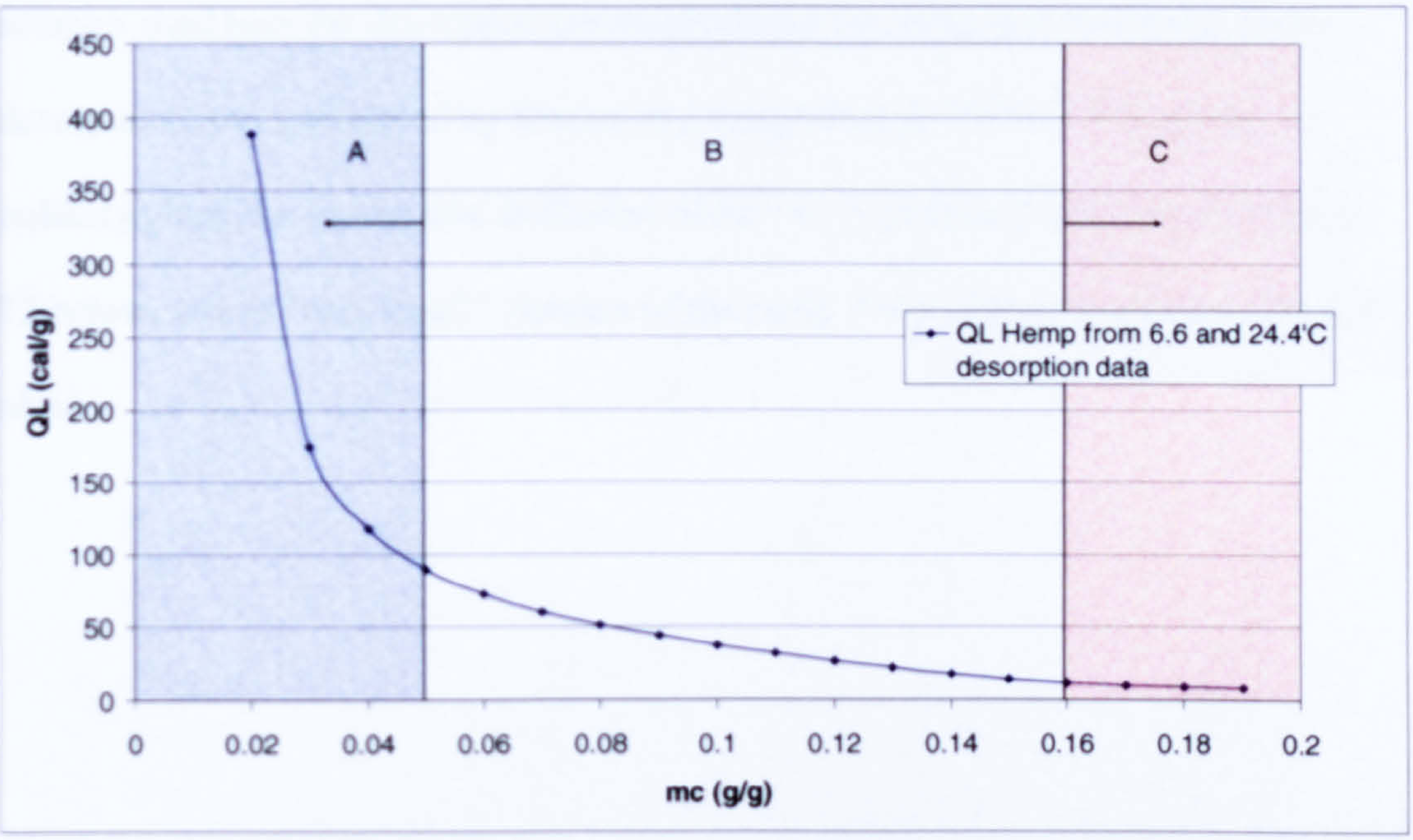


Figure 71 a graph to summarise the areas of most likely inaccuracy from the experimental procedure. Where B) is the area least likely to contain inaccuracies and A) and C) are the lower and upper areas (respectively) more likely to contain inaccuracies

7.5.3 Use of desorption curves

After the link between the data used in Stamm and Loughbrough (1934, presented in U.S. Forest Products Laboratory, 1974) and in Skaar (1972) was noticed, it was expected that the use of a "oscillating desorption curves" would be required to calculate the differential heats of wetting. However in this experimentation where "average sorption curves" and desorption curves were compared it was found that desorption curves from the DVS produced a more accurate figure than that of the average sorption. It is not known why this has occurred though it is noted that the sample weight used here was far smaller than that described by Stamm and Loughbrough (1934) *i.e.* around 4 mg rather than 100-125g. It was noted by Stamm and Loughbrough (1934) that the 100-125g samples they had used “were sufficiently large to permit the setting up of moisture gradients across the sections during the process of drying”. It may be that in the absence of such a gradient in the small samples used here the desorption curves produced are more akin to the oscillating desorption curves produced by Stamm and Loughbrough (1934). Though this is unlikely given the description in Stamm of the two experiments presented in Figure 72 below, where “very small” samples of the same wood produced notably different plots.

It is more likely however, that it is the ***relationship*** between the desorption curves produced (at different temperatures) that produce the similar results. The "average sorption curves" produced here are an average of both the ***ad***sorption and ***de***sorption curves. It was noted that there was ***no*** difference observed at different temperatures between the ***ad***sorption curves (only the ***de***sorption curves). As such the production of these "average sorption curves" will result in a curve with only ***halve*** the observed difference seen between the desorption curves. It is thus considered that the ***relationship*** between desorption curves produced here and the oscillating desorption curves of Stamm and Loughbrough (1943) are comparable, rather than the type of plots themselves. Specifically, it is the observed distance between the isotherms that governs the differential heat of wetting figures studied here.

7.5.4 The effect of the integral heat of wetting on an LCA

In terms of the overall bearing on the established LCA, the calculated *in situ* integral heat of wetting calculated for hemp fibre, it is unlikely to make any notable difference in terms of environmental impact. This is because the quantity of heat involved is small, thus it is unlikely to be noticed by the dwellings occupants, who are thus unlikely to alter their heating usage, which in turn would have made a difference to the energy used by the home and the LCA.

It is however noted that in different building systems where larger amount of natural fibres are used (*e.g.* where hemp based insulation is used in wall systems, or perhaps in hemp lime systems or even un-treated internal timber panelling) it is possible that the effects of the integral heat of wetting discussed here, would have an effect on the heat budget of the building. This requires further work, but is outside the scope of the present study.

7.5.5 Comparison to other works

It was noted in the Literature Review of this water sorption section (Chapter 5) that a spread of ***ad***sorption isotherms at different temperatures was observed by some researchers for various natural materials; however this was not observed with the materials studied here. Without repeating the experiments of others using the same methods it is hard to say why this difference was observed. It was noted however that there is a large difference in the scale of the experiments used. For example, the work of Stromdahl (2000) describes the use of large chambers with many samples being acclimatised at any one time. It is possible that in this environment that there may be a very slight oscillations in RH near each fibre sample as the humidity controlled air is not a linear flow across the sample thus there may be some discrepancy between the measured RH (and its variability) and that experienced by the fibre samples. If any oscillation is experienced then a form of "oscilating ***ad***sorption curve" will be produced.

If any slight oscillation were to occur, it is also noted that in both Stromdahl's and other experiments where salt or acid solutions are used, increased moisture content drift may be experienced, especially where the sample is left for an extended time to reach "equilibrium" rather than the reading being taken when a certain rate of change has been reached (*i.e.* the dm/dt set for each DVS experiment).

This would not necessarily mean that the plots produced by these other methods are "wrong" but it would mean that there could be a discrepancy over the terminology used to describe the "adsorption curves", and that a difference in adsorption curves with temperature would be observed as there would be a small contribution of desorption associated with the figures.

7.6 Conclusions and Recommendations

The main conclusions arising from this section are as follows:

- Adapting the thermodynamic method (described by Skaar, 1972) for use with DVS data, appears to give reasonable heat of wetting values when desorption curves are used.

- The method however, exhibits possible inaccuracies at very low moisture contents, and also where moisture contents approach fibre saturation point.

- In terms of the initial LCA the (integral) heat of wetting of hemp fibre is unlikely to make a difference to the overall environmental impact of a hemp based insulation material over its life cycle.

- If very large quantities of a natural fibre are used in a building exposed to fluctuations in RH, the (integral) heat of wetting may produce a notable difference in the internal temperature of the building.

It is recommended from this study in terms of future work that large numbers of replicate samples are studied using the DVS analyser at different temperatures (preferably using the same samples for each temperature). This would provide a more robust database that could be averaged out to produce more reliable calculations regarding the differential and integral heat of wetting. It is also recommended that a large amount of low RH readings (and thus low moisture content) below 15% RH and also high RHs above 85% RH are taken (for example, in 2% RH increments) as these are areas highlighted as more likely to contain inaccuracies. This work was not possible during this study due to time constraints, as for example using one DVS analyser this work would take a minimum of one year's study if 10-15 repeats at 4 different temperatures for 2 fibre types were to be considered.

It is also recommended that more data is needed from "real life" uses of the insulation material to gauge whether it has an effect on the occupants in terms of their comfort. For example even if the heat of wetting is not noticed by the occupants, is the simple adsorption of water vapour is likely to make the occupants more comfortable or less likely to feel a "chill"? This work would require very costly large scale experiments but is probably the only way of scientifically gauging the materials' effect on a comparable LCA.

The ability of natural fibres to adsorb and desorb moisture is an important property that can be used to provide a passive environmental control system if used appropriately. The proper use of such materials requires further research.

8 Final Conclusions and Recommendations for Further Work

8.1 Introduction

The aim of this chapter is to summarise the main conclusions from the studies presented in this thesis. This chapter also makes suggestions for further work that could build on the knowledge gained from the work presented here and investigate some of the issues that arose.

8.2 Summary of the main conclusions

The results of the Life Cycle Assessment section of this study in ***Chapter 3***, displayed both advantages and some disadvantages from the NFI materials when compared to the provided benchmark mineral wool product. A major finding for example, was that the NFI materials perform particularly well against the benchmark products in terms of GWP. This was mainly due to the renewable carbon sequestered in the material withdrawing CO_2 from the atmosphere.

While the end of life scenarios studied did show a release of some of the sequestered carbon, only a portion of the total amount was released in landfilling and composting.

The issue of CO_2 sequestration in renewable materials was highlighted as an important area of study. LCAs of renewable materials that do not include this calculation are missing potentially large positive environmental contributions.

Highlighted as part of the sensitivity analysis in ***Chapter 4***, was the issue of standardising secondary dataset usage across all products. This was deemed necessary as independently produced secondary datasets often present different impacts for the same or similar materials and processes. Though the use of similar secondary data was maintained within the natural fibre insulation product LCAs, it was apparent that similar datasets were likely not to have been used in the aggregated benchmark dataset. Though this does not invalidate any comparisons it does raise the point that a great deal of consideration should be used when doing so, particularly in which impact categories are compared. It is thus noted that taking the results presented here for commercial product comparisons is not recommended.

Marginal analysis was used in ***Chapter 4***, to quantify the environmental impacts contributed to by each sub-process and material used in the production of the NFI materials. It was shown that both of the NFI products studied shared similar environmental burdens from the polyester binders used and also through the direct and indirect use of fossil fuels. The comparatively high use of fossil fuels is seen as an inherent problem with any smaller scale manufacture. As part of the optimization study that followed, the potential of a hemp-based product using larger scale processing was shown with vastly reduced energy usage. The larger scale machinery that was studied was that of standard technology and on a relatively small scale to which the benchmark product was produced. It was considered that use of larger scale or more efficient bespoke machinery could hold the key to far greater reductions in environmental impact.

8.2.1 Conclusions regarding the effect of water sorption on the LCA results

All the insulation products studied will save a substantial amount of operating energy in use. As part of this function they will also recoup the embodied energy needed for manufacture (and the environmental impacts of the energy production) several times over. However, this is only true if the assumption that they will perform the same task (in the same way) during the product's life is correct. One notable characteristic of natural fibre materials that differs from most synthetic materials is that of water sorption.

In ***Chapter 5*** a number of water sorption characteristics were discussed that raised questions over the effect of moisture in the LCA of natural fibre insulation materials. The work of Padfield (1998) showed that the adsorption of water vapour does not effect the thermal conductivity in natural fibre insulation any differently to that of mineral based materials, *i.e.* no change is noted until fibre saturation point in the natural fibres (and "condensation" on the mineral fibres) has most likely occurred. Hence further studies in this particular area were considered unlikely to produce a different outcome to the LCA results and were therefore ruled out.

It was also considered that the quantities of heat energy associated with water sorption (*i.e.* the heat of wetting - the heat released due to moisture adsorption and heat absorbed during moisture desorption) may affect a NFI products' performance.

Especially over the 60 year *in situ* performance that was modelled in the LCA, if the quantities of heat energy involved were found to be significant.

In terms of the initial LCA where a standard thickness of insulation was studied, the integral heat of wetting of hemp fibre (studied in ***Chapter 7***) was found unlikely to make a difference to the overall environmental impact. However, it was considered that if larger quantities of a natural fibre are used in a building exposed to fluctuations in RH, the heat of wetting may produce a notable difference in the internal temperature of the building.

8.2.2 Conclusions regarding the use of dynamic vapour sorption

Chapter 6 the use of the DVS analyser provided very smooth adsorption and desorption curves for a variety of natural fibres. This indicated that the data produced was of a reliable nature. It was also found that samples of natural fibres as small as 4mg could be used satisfactorily in the DVS analyser due to the large quantity of water adsorbed. A reduction in the quantity of data collection points between 10% and 80% RH in order to speed up data collection, appeared to still provide smooth and comparable sorption curves. However, it was noted that for comparisons between hysteresis plots a larger number of data points should be considered.

Adapting the thermodynamic method of calculating the integral heat of wetting (described by Skaar, 1972) for use with DVS data, appeared to give reasonable heat of wetting values, but only when desorption curves were used. The method did exhibit possible inaccuracies at very low moisture contents, and also where moisture contents approach fibre saturation point. This was not however considered to be a problem for the calculations presented in this study, due to the limited RH fluctuation studied.

8.3 Recommended further work

It is recommended that future LCAs concerning renewable materials should consider the quantities of CO_2 sequestered in the product. This is of particular importance especially when considering that global warming is caused by the quantity of CO_2 (and other "greenhouse" gasses) in the atmosphere at a given time. Thus, for every second that CO_2 is sequestered by a renewable material global warming to some extent is mitigated. If an LCA does not include this sequestration then this environmental benefit is not revealed.

In a more commercial sense, further work studying reduced energy technologies is highly recommended in order to realise the potential of "small scale" natural fibre products as shown in the optimization study of this report. Though this recommendation is made with reference to insulation products it is thought that a great deal of other renewable and non-renewable material based products would benefit from this work.

The ability of natural fibres to adsorb and desorb moisture is an important property that could potentially be used to provide a passive environmental control system if used appropriately. The proper use of such materials requires further research. In particular more data is needed from "real life" uses of the insulation material to gauge whether it has an effect on the occupants in terms of their comfort. For example even if the heat of wetting is not noticed by the occupants, is the simple adsorption of water vapour is likely to make the occupants more comfortable or less likely to feel a “chill” causing them to use less energy if less heating is required. This work would require very costly large scale experiments or survey, but is probably the only way of scientifically gauging the materials’ performance in these areas and its effect on comparable LCAs.

With regard to studies of water sorption in natural fibres, it is recommended that large numbers of replicate samples are studied using the DVS analyser at different temperatures (preferably using the same samples for each temperature). This would provide a more robust database that could be averaged and statistically analysed to produce more reliable calculations regarding the heat of wetting. It is also recommended that a large amount of low RH readings (and thus low moisture content) below 15% RH and also high RHs above 85% RH are taken (*e.g.*, in 2% RH increments) as these are areas highlighted as more likely to contain inaccuracies.

Regarding the possible correlations observed between lignin percentage and moisture sorption, it is also recommended that the use of “solute exclusion” (to study the available micro pore sizes) and “deuterium exchange” (to study the quantity of available hydroxyl groups) may also provide useful data for further studies in this area.

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N.B. where the reference has been accessed from a web site the date provided is the date accessed rather than the date published.

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10 Appendix

Appendix I: Table 15 below shows all the ***cradle to installation*** results calculated using the CML 2 baseline 2000 V2.1 on a ***Functional Unit*** basis

Table 15 the cradle to installation results on a *Functional Unit* basis for Thermafleece and Isonat

Impact category	Unit	Thermafleece	Isonat
abiotic depletion	kg Sb eq	0.0254	0.0527
global warming (GWP100)	kg CO_2 eq	-1.82	2.72
ozone layer depletion (ODP)	kg CFC-11 eq	8.36E-07	2.02E-06
human toxicity	kg 1,4-DB eq	2.55	3.29
fresh water aquatic ecotox.	kg 1,4-DB eq	0.564	0.429
terrestrial ecotoxicity	kg 1,4-DB eq	0.0329	0.0371
photochemical oxidation	kg C_2H_2	0.00167	0.00214
acidification	kg SO_2 eq	0.047	0.0641
eutrophication	kg PO_4--- eq	0.00652	0.0104

Appendix II: Table 16 below shows all the ***cradle to installation*** results calculated using the CML 2 baseline 2000 V2.1 on a ***per kg basis***.

N.B. This data has been presented on a per kg basis as many other general resources will present data in this way. It must be noted that only with a ***great deal of caution*** *and the understanding of the processes included in each set of data should it the data presented here be used for any comparisons with external data. It should only be compared to data analysed with identical or perfectly comparable system boundaries and assumptions.*

Table 16 the cradle to installation results on a *per kilo* basis for Thermafleece and Isonat

Impact category	Unit	Thermafleece	Isonat
abiotic depletion	kg Sb eq	0.0045	0.0067
global warming (GWP100)	kg CO_2 eq	-0.3233	0.3454
ozone layer depletion (ODP)	kg CFC-11 eq	0.0000	0.0000
human toxicity	kg 1,4-DB eq	0.4529	0.4178
fresh water aquatic ecotox.	kg 1,4-DB eq	0.1002	0.0545
terrestrial ecotoxicity	kg 1,4-DB eq	0.0058	0.0047
photochemical oxidation	kg C_2H_2	0.0003	0.0003
acidification	kg SO_2 eq	0.0083	0.0081
eutrophication	kg PO_4--- eq	0.0012	0.0013

Appendix III: Table 17 below shows the CML baseline impacts of the contributing processes and materials for a ***cradle to installation*** analysis of the Thermafleece product is presented here on a ***per kg basis***.

Table 17 marginal analysis results for Thermafleece using CML basline impacts on a *per kg basis*

Impact category	**Abiotic depletion**	**Global warming (GWP100)**	**Ozone layer depletion (ODP)**	**Human toxicity**	**Fresh water aquatic ecotox.**	**Terrestrial ecotoxicity**	**photochemical oxidation**	**acidification**	**eutrophication**
Unit	*kg Sb eq*	*kg CO2 eq*	*kg CFC-11 eq*	*kg 1,4-DB eq*	*kg 1,4-DB eq*	*kg 1,4-DB eq*	*kg C2H2 eq*	*kg SO2 eq*	*kg PO4--- eq*
Total	**0.00451**	**-0.323**	**1.48E-07**	**0.453**	**0.1**	**0.00584**	**0.000296**	**0.00835**	**0.00116**
Clean, Raw Wool	0.0017	-1.53	0	0.106	0.0332	0.00107	0	0.00141	0.000145
Packaging film	0	0.0681	0	0.0106	0.00294	0.000398	0	0.000666	0
Bi-component Polyester	0.00065	0.455	0	0.182	0.0312	0.00283	0.000124	0.00325	0.000595
Heat gas	0.00182	0.205	0	0.0221	0.000173	0.00019	0.000011	0.000229	0
Electricity, medium voltage	0	0.333	0	0.0897	0.0298	0.00111	0	0.00122	0
Transport total	0.000906	0.145	1.22E-07	0.0356	0.00231	0.000113	0	0.0017	0.000277
Recycling PP	-0.00056	0.00123	0	0.00695	0.000426	0.000133	0	-0.00012	0

Appendix IV: Table 18 below shows the CML baseline impacts of the contributing processes and materials for a ***cradle to installation*** analysis of the Isonat product is presented here on a ***per kg basis***.

Table 18 marginal analysis results for Isonat using CML baseline impacts on a *per kg basis*

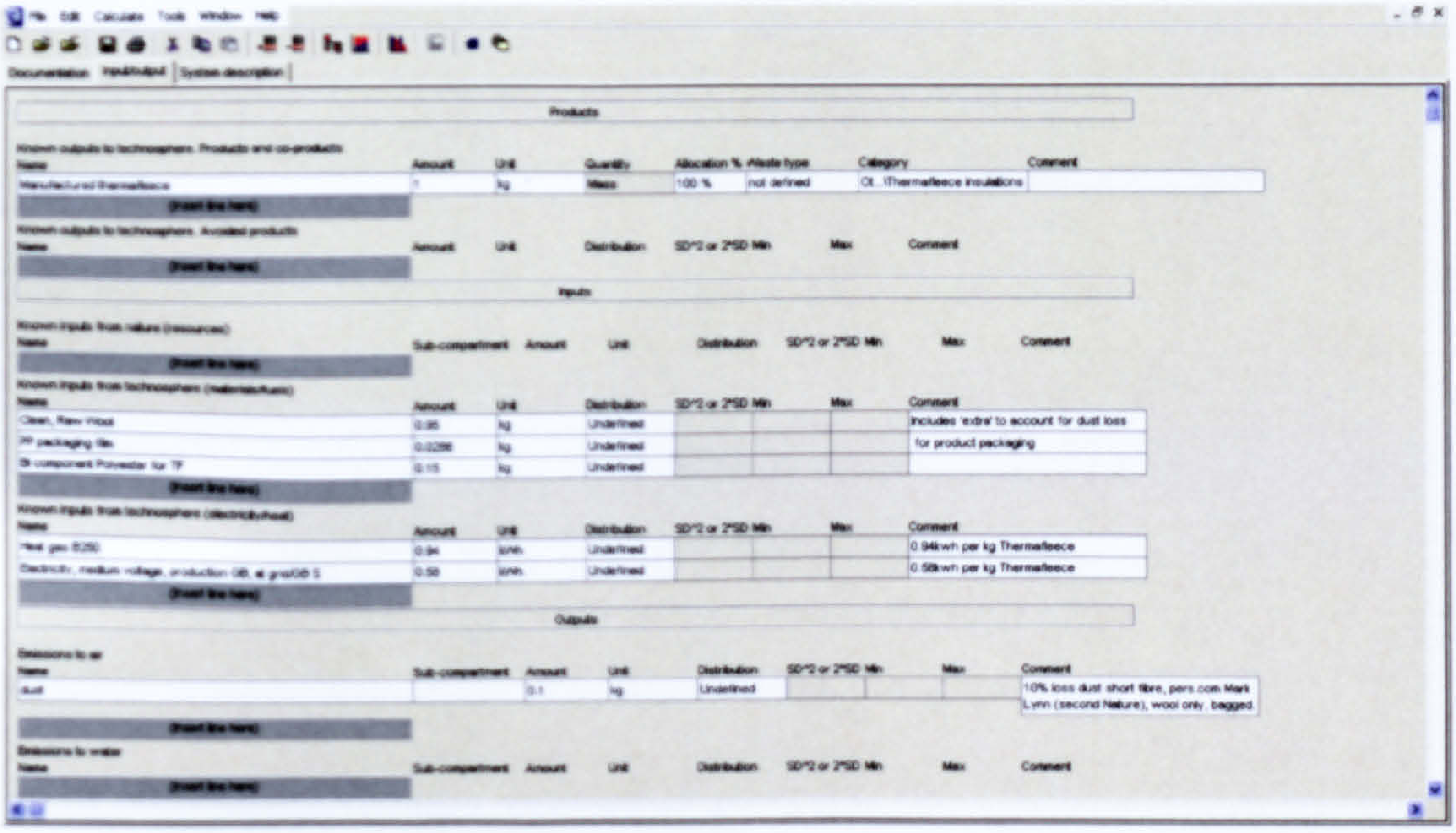
Impact category	**abiotic depletion**	**global warming (GWP100)**	**ozone layer depletion (ODP)**	**human toxicity**	**fresh water aquatic ecotox.**	**terrestrial ecotoxicity**	**photochemical oxidation**	**acidification**	**eutrophication**
Unit	*kg Sb eq*	*kg CO2 eq*	*kg CFC-11 eq*	*kg 1,4-DB eq*	*kg 1,4-DB eq*	*kg 1,4-DB eq*	*kg C2H2 eq*	*kg SO2 eq*	*kg PO4-- eq*
Total	**0.00669**	**0.345**	**2.56E-07**	**0.418**	**0.0545**	**0.00471**	**0.000272**	**0.00814**	**0.00132**
Hemp fibre production	0	-0.486	0	0.0708	0.01	0.000421	0	0.000437	0
Cotton fibres recycled	0	-0.511	0	0.000432	0	0	0	0	0
Bi-component Polyester	0.00065	0.455	0	0.182	0.0312	0.00283	0.000124	0.00325	0.000595
Flame retardant	0	0.0426	0	0.0332	0.00431	0.000391	0	0.000155	0
Kraft paper, unbleached	0	0	0	0	0	0	0	0	0
Packaging film	0	0.0648	0	0.01072	0.003076	0.000364	0	0.000695	0
Electricity, medium voltage	0	0.0139	0	0.00755	0.00176	4.10E-05	3.12E-06	8.82E-05	6.51E-06
Heat gas	0.00448	0.506	0	0.0546	0.000428	0.000469	2.70E-05	0.000565	6.37E-05
Transport total	0.00164	0.263	2.21E-07	0.0599	0.00411	0.000157	7.40E-05	0.00297	0.000534
Recycling ECCS steel	0	-0.014	0	-0.00112	-0.00053	0	0	0	0
Recycling PP	0	0	0	0.000204	0	0	0	0	0
Landfill PE	0	0.0123	0	0	0	0	0	0	0

Appendix V: The "Chlorite Holocellulose" method as described by Han and Rowell (1997):

To 2.5 g of oven dry sample add 80 ml of hot distilled water. 0.5 ml acetic acid and 1 g of sodium chlorite in a 250 ml Erlenmeyer flask. An optional 25 ml Erlenmeyer flask is inverted in the neck of the reaction flask. The mixture is heated on a water bath at 70°C. after 60 min, 0.5 ml of acetic acid and 1 g of sodium chlorite are added with shaking. The delignification process degrades some of the polysaccharides, and the application of excess chloriting should be avoided.

Addition of 0.5 ml of acetic acid and 1 g of sodium chlorite is repeated until the fibres are completely separated from lignin. The reaction is then cooled and filtered using filter paper and a Buchner funnel until the yellow colour (the colour of the holocellulose is white) and the odour of chlorine dioxide are removed. The lignin content of the original sample can be determined by subtracting the oven dry weight of the de-lignified holocellulose from the original oven dry weight.

Appendix VI: Example screen print from the SimaPro 4 program looking at the example process of Manufactured Thermafleece.



Products

Known outputs to technosphere. Products and co-products

Name	Amount	Unit	Quantity	Allocation %	Waste type	Category	Comment
Manufactured thermafleece	1	kg	Mass	100 %	not defined	Ot...\Thermafleece insulations	

(Insert line here)

Known outputs to technosphere. Avoided products

Name	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment

(Insert line here)

Inputs

Known inputs from nature (resources)

Name	Sub-compartment	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment

(Insert line here)

Known inputs from technosphere (materials/fuels)

Name	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
Clean, Raw Wool	0.95	kg	Undefined				Includes 'extra' to account for dust loss
PP packaging film	0.0288	kg	Undefined				for product packaging
Bi-component Polyester for TF	0.15	kg	Undefined				

(Insert line here)

Known inputs from technosphere (electricity/heat)

Name	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
Heat gas B250	0.94	kWh	Undefined				0.94kwh per kg Thermafleece
Electricity, medium voltage, production GB, at grid/GB S	0.58	kWh	Undefined				0.58kwh per kg Thermafleece

(Insert line here)

Outputs

Emissions to air

Name	Sub-compartment	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment
dust		0.1	kg	Undefined				10% loss dust short fibre, pers.com Mark Lynn (second Nature), wool only, bagged.

(Insert line here)

Emissions to water

Name	Sub-compartment	Amount	Unit	Distribution	SD^2 or 2*SD	Min	Max	Comment

(Insert line here)