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Front Cover: Wassily Leontief, founder of the Input-Output Analysis. The equations show the way of formulating the Leontief problem. Further details see the Editorial on p. 1. Cover idea: Sangwon Suh, Subject Editor, Section Input-Output and Hybrid LCA. Cover design: Edwin Grondinger (e.grondinger@abc-media.de).

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LCA Case Studies

A Comparative Life Cycle Assessment of Building Insulation Products made of Stone Wool, Paper Wool and Flax

Part 1: Background, Goal and Scope, Life Cycle Inventory, Impact Assessment and Interpretation

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Preamble. Insulation of buildings is an important technology for saving heating energy and for a sustainable development. The results of a comparative LCA study of three insulation products applied for roof insulation are summarised in two parts. The products selected are based on HT stone wool representing traditional products - flax representing crop grown products and paper wool representing recycled products, respectively. Although the three materials have vastly different life cycles, they yet fulfil the same function; the methodology used should be of general interest.

Part 1 of the paper contains the project background, the goal and scope definition and three life cycle assessments for the three individual products, with a detailed inventory analysis, impact assessment, sensitivity analysis and interpretation. The actual comparison of the results from the three individual life cycle assessments is presented in **Part 2.** An attempt is made to answer the question of whether the biological products flax and paper wool are more environmentally preferable than the mineral product stone wool representing more traditional insulation materials.

In general, paper wool has the lowest global and regional environmental impacts, and flax insulation the highest, with stone wool falling in between. A notable exception is the total energy use, where stone wool has the lowest consumption followed by cellulose and flax. The study also addresses occupational health issues using an approach similar to that for risk assessment. Here, the less biopersistent HT stone wool products are seen to be the safest alternatives, because of a low potential for exposure, sufficient animal testing, and the obvious absence of carcinogenic properties.

It must be recognised that insulation of buildings saves more than 100 times the environmental impacts associated with the production and disposal of the products used for insulation. Compared to that and the inherent uncertainties in the LCA, the differences between the investigated products are of minor environmental significance. Therefore, the main conclusion demonstrated in the study is that the quality and fitness of an insulation product is the most important aspect in the life cycle of insulation materials.

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Abstract

Insulation of buildings in order to save heating energy is an important technology for enabling sustainable development. This paper summarises the results of a comparative LCA study according to ISO 14040 standard series of HT stone wool, flax representing crop grown products and paper wool representing recycled products applied for roof insulation. As the three materials have vastly different lifecycles, yet fulfil the same function cycles, the methodology used should be of general interest. Part 1 consists of the project background, goal and scope definition, a detailed life cycle inventory analysis with sensitivity analysis, impact assessment and interpretation. The actual comparison of the results from the life cycle assessments of the three products, in which an attempt is made to answer the question of whether the biological products flax and paper wool are more environmentally preferable than the mineral product stone wool representing more traditional insulation materials, is discussed in Part 2.

Keywords: Building insulation; case study; flax; goal and scope; LCA; LCI; paper wool; stone wool

1 Background

Insulation of buildings is a major sustainable technology to save heating energy and thereby contributing to conservation of energy resources and lowering of associated burdens of air pollution from the combustion of fossil fuels.

In 1995–96, an average household in the EU used about 50,000 MJ for heating purposes, corresponding to about 68% of the total energy consumption in the households, and 40% of the total energy consumption in EU. Portuguese households have the lowest consumption for heating purposes (10,000 MJ or 29% of total), while Luxembourg has the highest consumption (122,000 MJ or 73% of total). In countries like Belgium, Germany and Austria, more than 75% of the energy consumption in households is used for heating purposes [1].

For many years, a few materials have dominated the European market for insulation products, with the majority of the market covered by mineral wool (glass wool and stone wool). Polymer-based materials like expanded polystyrene (EPS), extruded polystyrene (XPS) and polyurethane (PUR) have also been used and, during the recent years, a number of 'new' materials have emerged on the market.

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It is difficult to obtain a precise overview of the total European market as well as the individual shares of the materials. The West European market is characterised by a larger mineral wool market share in the north, whereas plastic foam insulation has a higher market share in the south. The Western Europe building insulation market in 1994 of a value of approximately 3.3 billion euros has been estimated to [2]:

– Mineral wool: Glass	27%
– Mineral wool: Stone	30%
– Foam plastics	40%
– Other materials	3%

2 Introduction

Many people believe that the emerging insulation products based on biological resources (cellulose), such as flax and paper wool, are much more environmentally friendly than a product based on natural mineral resources such as stone wool. This belief may, however, be unfounded. For a proper judgement it is necessary to compare the products and their impacts over the full life cycle. In two parts, this paper summarises the results of a comparative life cycle assessment (LCA) for the following three insulation products for attics:

- HT Stone wool insulation product based on natural minerals and recycled post-production waste materials. Binder and impregnation oil are added to achieve requested and desired technical properties.
- Flax insulation product based on flax grown in Europe. Polyester, diammonium hydrogen phosphate and borax are added to achieve the requested and desired technical properties.
- Paper wool insulation product based on shredded newsprint paper. Aluminium hydroxide, borax and/or boric acid are added to achieve the requested and desired technical properties.

The full study will be printed and be publicly available on the website: www.dk-teknik.dk.

A number of LCA-studies of insulation products have already been performed. The best-known ones are probably the documents with a life cycle screening of the environmental impacts as a basis for development of eco-label criteria for the European eco-labelling scheme [3,4]. These reports are, however, of varying quality for the single materials, simply because the information necessary to produce a consistent overview of good quality was not available at the time of the study.

Many producers have established life cycle assessments for their own products, often relating to a specific application. Although the studies are more recent than the eco-labelling studies, they still use basic information of relatively old age. For example, the first BUWAL-studies from 1991 are a key source of information in many reports. Some of these studies were not published in open literature and do not reflect the progress in LCA-methodology that has been achieved since the publication of the ISO 14040 standard series (ISO 14040–14043).

It is concluded from the survey of the available literature, that only a small part is relevant for a discussion of the findings in the present study. In practice, the most relevant report was an (unpublished) LCA of stone wool conducted by Rockwool Limited, U.K., in 1998 using a LCA method and data that fulfil the requirements in the ISO 14040 standard series to a very large extent [5]. The results published in that report have been compared with those from the present study, which is primarily based on Danish production of stone wool with a slightly different production process, thereby giving an indication of the representativity of either study. For flax and paper wool insulation, a Danish report from the Building Research Institute was used to focus the data collection and data treatment [6]. However, the documentation and presentation of the results in the Danish report are different and do not give sufficient opportunity for a proper comparison between the results.

3 Goal and Scope Definition

The objective of the LCA is a cradle to grave assessment of three products used for insulation of a roof taking into consideration their very different life cycles by using the best available data on the European level. The products are based on the three materials stone wool, flax and paper wool, respectively. The study aimed for compliance with the ISO 14040 series of LCA standards.

3.1 Fitness for use

The main purpose of insulation materials is to decrease the heat loss from buildings and save energy and costs. During the lifetime of a building the energy savings will be considerable and far higher than the energy consumption during the production of the material. The three insulation materials studied are fit for use but they have different basic properties, and in the practical application in the building the durability and performance during building life may also be different. Some important characteristics are as follows:

- The insulation material must fit and fill out the construction without air gaps, and ideally it should remain unchanged in all three dimensions during the building lifetime,
- The material must be stable to moisture and resistant to biological attack,
- The material shall not emit or radiate substances in hazardous concentrations to the indoor climate,
- The fire properties of insulation materials are vital. The classification and labelling in the present Danish building regulations are:
  - Stone wool with label 'A1' and 'A2' (non combustible),
  - Paper wool with expected label 'B-E' depending on amount, type and content of flame retardant,
  - Flax with expected label 'C-E' depending on amount, type and content of flame retardant.

3.2 Functional unit

The functional unit is defined in the ISO 14040 standard as 'the quantified performance of a product system for use as a reference unit in a life cycle assessment study'. With respect to thermal insulation products, the thermal resistance R, measured in m^2K/W, has been generally accepted as a meaningful and operational functional unit. On the one hand, it gives information about the amount of insulation material that is necessary to perform a certain thermal resistance over the insulation lifetime. On the other hand, it makes it possible to balance the environmental impacts during production, installation and disposal with the savings that can be achieved during the use phase of the insulation product.

The discussion concerning the functional unit in the nineties has been on how to handle durability, the length of the use phase (25, 50, 60, 75 years or building life) and which thermal resistance (R-value) to choose.

In this study, the functional unit was defined according to a proposal from Council for European Producers of Materials for Construction (CEPMC) [7]. CEPMC favours 50 years use phase and an R-value of 1 m^2K/W. The same unit was used in the criteria for EU ecolabelling of insulation materials. The Functional Unit (F.U.) in kg is accordingly defined as:

$$\text{F.U.} = R \text{ x } \lambda_{design} \text{ x } d \text{ x } A \qquad (1)$$

Where R is the thermal resistance as 1 m^2 x K/W; λ is the thermal conductivity measured as W/m x K ($\lambda_{design} = \lambda_{declared}$); d is the density of the insulation product in kg/m^3; A is the area in m^2, here $1m^2$; K is °K; W is Watt.

Based on the above definition of the functional unit and the considerations regarding functionality, the actual amount of insulation material that must be installed can be calculated (**Table 1**).

This functional unit does not take into account the possible need for other construction materials, but focuses solely on the environmental and insulating properties of the materials. This means that the conclusions are not valid for applications, in which other construction materials are necessary to fulfil building regulatory demands.

3.3 System boundaries

In general, the system boundaries are defined by current conditions on the Western European market. Where possible, the system boundaries are determined by a marginal approach/system expansion as outlined in the Danish LCA-methodology project [8]. The main principle in this is that only those processes that are affected by the demand for an extra amount of product are included. As an example, the marginal approach demonstrates that in order to produce paper wool insulation, additional virgin pulp is needed in order to cover the demand for newsprint paper fibers in the whole market. The general approach was not feasible or relevant for all aspects relating to the general system boundaries, the most prominent exceptions being addressed below:

- The use phase is not included in the results, because the impacts (or avoidance of same) are similar for all three materials. It can be calculated that in a typical application, insulation will save over 100 times the impacts from production and disposal, irrespective of the material used. It is thus readily concluded that the use of insulation is overwhelmingly beneficial for the environment. Therefore, the paper focuses on an examination of the differences between the products with respect to their production, installation and disposal, because these are the basis for the choice between the materials.
- The production of flax and paper wool is regarded as CO_2-neutral, i.e. that the same amount is taken up during growth as is emitted when the products are disposed of by incineration or composting. If landfilled, some of the carbon will be emitted as methane, giving a higher contribution to global warming. Recycling in low-grade applications may also cause methane emissions, but this has been disregarded in the sensitivity analysis, because it will probably be after the 100 years horizon for global warming potential applied in the study.
- Electricity used in different processes is – where possible – assumed to be generated as average European base load as described by Frees and Weidema [9]. Due to different ways of reporting inventory information, this approach was not feasible for all processes, most notably the inventories reported by the Association of Plastics Manufacturers in Europe (APME) [10], and the inventory for newsprint production from the Finnish Pulp and Paper Institute, KCL.
- Due to heterogeneity in flax agricultural practices and results, average information on, e.g., yields and use of machinery was mixed with specific information regarding farming practices, e.g. with respect to consumption of fertilisers and pesticides. System expansion was used to account for co-production of seeds and shives in the main scenario, and the outcome was in a sensitivity analysis compared to the results obtained by using economic allocation.

Table 1: The functional unit (in kg) necessary to provide a thermal resistance of 1 m^2K/W for a use period of 50 years

Material	Lambda $_{design}$ mW/m °K	Density kg/m^3 (dry) [d]	Functional unit (kg)	Corresponding insulation thickness (settled); in mm
Stone wool batts	37[a]	32	1.184	37
Paper wool granulate	40[b]	32 (dried) [c]	1.280 [g]	40
Flax rolls	42[e]	30 (dried) [f]	1.260	42

[a] EC-Certificate number 1073-CPD-137

[b] Producer information; Dansk Ekofiber Oct. 2002 lambda declared = 40 mW/mK

[c] Initial density in ambient conditions 33–35.2 kg/m3, depending on lambda measurement system.

[d] Cellulose based materials present a special case with respect to density. The lambda and density is measured on dried samples whereas the products are used with the 'natural moisture content', which for paper wool and flax is in the region of 10–14% moisture.

[e] Lambda $_{design = declared}$ estimate for 30 kg/m3 Flax, based on information from Dansk Naturisolering (http://www.naturisolering.dk/horfiber1.htm)

[f] The ambient moisture content is given by Dansk Naturisolering at 80% RF to approx. 15%

[g] Includes 25% extra material to compensate for settling

Also, the marginal approach could not be used to determine how insulation waste will be managed 50 years from now. Six disposal options seem more or less realistic:

- Recycling or re-use as insulation material
- Recycling in low-grade applications
- Recycling by composting (not realistic for stone wool)
- Incineration with energy recovery (not realistic for stone wool)
- Incineration without energy recovery (not realistic for stone wool)
- Landfilling

Recycling or re-use as insulation material can be seen as a way to close the material cycle and avoid both production of new raw materials and generation of solid waste. Re-use cannot be recommended, unless certainty can be assured that the waste products are as fit for use as new products. Recycling to new products is a viable option for stone wool while for flax and stone wool there are practical problems associated with collection of the materials in the demolishing process and the subsequent recycling, either to new insulation products or in composting. Incineration with or without energy recovery is seen as a viable option for flax and paper wool, giving the possibility of utilising the inherent energy but, again, there are practical problems in keeping the fractions separated during the demolishing process. Landfilling is probably the most used disposal option in Europe, but will presumably be reduced in the future due to changes in regulations.

In the LCA, recycling in low-grade applications like road foundation was chosen as the base-case scenario for all three insulation materials. By recycling of insulation waste, consumption of other resources can be avoided. However, it was chosen to include neither positive nor negative impacts from the recycling process.

Obviously, this choice is disputable. Therefore, a sensitivity analysis was applied, examining the changes that can be observed if the inherent energy in flax and paper wool is utilised or if the materials are composted or landfilled. The following disposal scenarios were investigated:

- Paper wool:
  - 20% incineration/80% recycling
  - 20% landfilling/80% recycling
- Flax:
  - 20% incineration/80% recycling;
  - 20% landfilling/80% recycling;
  - 20% composting/80% recycling
- Stone wool:
  - 100% recycling to new products

The examined scenarios are primarily used to give an indication of which disposal option is the most favourable from an environmental point of view and, secondly, to indicate the importance of different disposal options in a life cycle perspective.

Packaging (LDPE foil) is included in the investigation. The APME database for LDPE was used to calculate the impacts from production and processing [11]. The following values for different disposal routes were assumed to give a representative picture of current European conditions:

– Energy recovery (incl. feedstock recycling):	25%
– Mechanical recycling:	15%
– Landfilling:	50%
– Incineration without energy recovery:	10%

For wooden pallets, it was assumed that each pallet is used twice, before being recycled for other purposes, e.g. as a fuel in small stoves in private homes. Half of the impacts from their production were ascribed to the stone wool system, but no credit was given for the inherent energy that eventually can be utilised.

Due to the relatively small amount of packaging being used, no sensitivity analysis was applied to examine the importance in more detail.

3.4 Inventory method and data

The programme used for the calculations was 'LCA Inventory Tool' (version 2.01) from CIT Ekologik in Sweden. It allows for a very flexible format of the basic inventory data to be entered, e.g. by having the possibility of using inventories where the emissions from extraction and combustion of energy sources were already included, or inventories where only process-related emissions were stated along with the consumption of energy sources, measured in MJ/kg or in kg/kg.

The study has aimed at achieving the best possible data quality. This has been done by an extensive search for relevant and recent literature data, and requests to the suppliers of the chemicals that are used in the three systems. Most of the data used for the calculations were established in this way. For some of the key materials and processes such data were neither available nor forthcoming, and therefore it was necessary to use information known to be of lower quality.

A wide variety of data sources have been used, e.g. open LCA databases such as APME Reports [10,12], BUWAL [13,14], and IVAM database [15] and information from suppliers to Rockwool A/S. Ammonium hydrogen carbonate was the only constituent for which specific information could not be found and, instead, surrogate data (for ammonia production) were used.

The data format suggested by the Council for European Producers of Materials for Construction (CEPMC) [7] for reporting of environmental information for building and construction materials was used as the basic element in the inventory reporting in the current study. The advantage of using this format is that it provides an easy overview of all interventions that are included in the quantitative impact assessment. At the same time, there are a number of drawbacks that are described in brief below:

- The format does not include the compounds that contribute to the impact categories that are handled qualitatively in the study and thus the tabulation does not provide a full overview
- The format requires that the use of different fossil fuels is divided into use of fuels for energy and for feedstock and reported in MJ as well as kg per functional unit, and, at the same time, the amount of electricity consumed must be quantified. For example, this requirement can not be fulfilled by the APME inventories for plastics. In these, the energy consumed is divided into three types (electricity, oil fuels, and other fuels) and distributed to four activities (fuel production and delivery, energy content in delivered fuel, energy use in transport, and feedstock energy), while another table distributes a number of different fuels on the

same activities, but gives no possibility of distinguishing between fuels used for electricity and for products. Thus, there may be small differences between the reported energy consumption measured in MJ/kg and kg fuels/kg. No efforts have been devoted to make an assessment of the relative and combined importance of the use of energy and other resources, the reason being that besides fossil fuels, the main part of the raw materials entering the life cycle of the three products are either renewable or abundant.

- The format only includes two types of waste, i.e. hazardous and non-hazardous waste. However, the different inventories used in the calculations holds in total 18 different types of waste as specified by the data suppliers. It must be assumed that this reflects different national traditions and regulations, as well as different levels of knowledge regarding which types of waste are actually produced in the activities. In order to follow the CEPMC-format as closely as possible, it is chosen to aggregate five waste categories (hazardous, chemical, regulated chemicals, radioactive and highly radioactive) under the heading 'hazardous waste'. The remaining categories are aggregated under the heading 'non-hazardous waste'.

3.5 Impact assessment method

A hybrid model is used to perform the impact assessment. A quantitative approach is applied to the impact categories where both good quality inventory data and internationally recognised impact assessment methods are available. Thus, equivalence factors from the CML [16] and EDIP [17] LCA-methods are used to quantify the contribution to global and regional impacts, the focus being on global warming, acidification, eutrophication and photo-oxidant creation potential. No indication has been found that any of the products contributes to depletion of the ozone layer, and this impact category is therefore omitted from the study.

The potential toxicological impacts from human exposures are addressed qualitatively, focusing on exposures in the working environment during installation and removal of the insulation, and, to a lesser extent, the indoor climate for users of the building. Quantitative LCA-methodology is not very suitable for this type of impact assessment, both because the exposure is almost exclusively restricted to the working environment and because calculation of toxic equivalence factors for fibers is associated with methodological problems that have not yet been fully developed. It should be recognized that in many product systems, the main contributions to human toxicity as assessed by conventional LCA-methodology are generally energy-related, e.g. in the form of emissions of SO_2, NO_x and heavy metals from combustion processes.

The impacts on local ecosystems are only addressed briefly, focusing on a semi-quantitative description of the environmental properties of the pesticides used in flax growing.

3.6 Allocation method

The ISO 14040 standard series prescribes that allocation should be avoided wherever possible, and that is best achieved by expansion of the system boundaries. Consequently, this is the approach that has been used in this study with a few exceptions as described.

3.7 Critical review

An external critical review was included in the original study starting from the Goal and Scope Definition and onwards. The critical reviewer, Dr. Dennis Postlethwaite, was invited to be co-author of this summary paper.

4 Results for Stone Wool

The overall process for production of stone wool comprises the following main sequence: Acquisition of rocks/stones → molten stone → spun fibers → stone wool fiber mats ('batts'). A more detailed overview of the activities can be found in **Fig. 1**.

The main raw materials for stone wool are natural stones (diabase, Gotland stone, lime stone, bauxite) accounting for about 77% of the raw materials for briquettes, while the remaining 23% are industrial waste materials, e.g. from cement and steel production pre- and post-consumer stone wool waste.

The binder is produced on-site from a number of chemicals and accounts for about 8% of the overall material input to the production process. Phenol, formaldehyde and urea are mixed with a catalyst in a reactor. Subsequently, ammonia and silane are added in a precipitator, where the catalyst is recovered for recycling.

The final production in the blast furnace oven includes a number of activities. Binder and impregnation oil are added to the melted rock, which is poured on to rotating wheels and fibers are formed under the influence of a powerful airflow. The product is cured in a polymerisation chamber and, finally, the stone wool is cut into the desired dimensions and packaged in polyethylene foil.

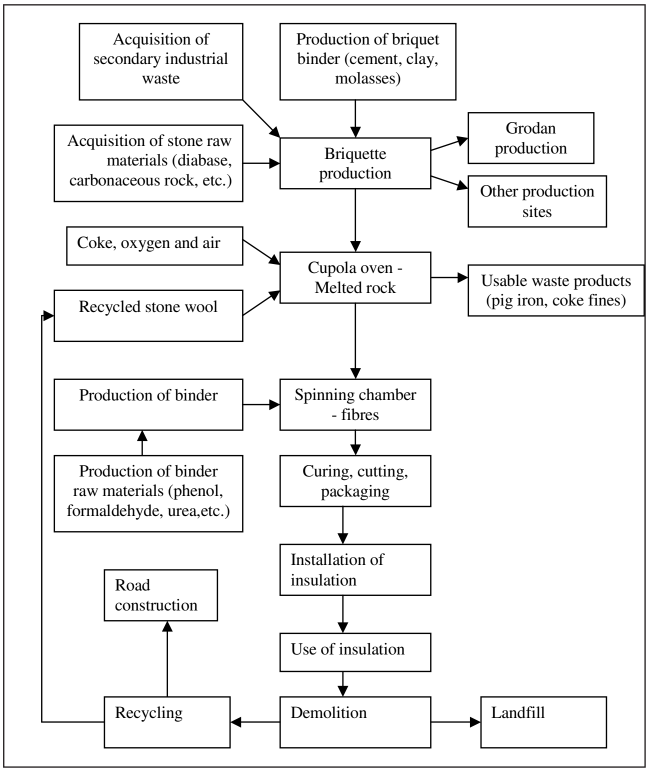

Fig. 1: Flow diagram for Stone wool

The inventory for stone wool production has been established by using up-to-date information from one Danish production facility. The recipe used at this production facility is almost identical to recipes at other facilities throughout Europe, and the results can therefore be regarded as representative at the European level, with the limitations mentioned in the interpretation section.

An environmental account for the production facility, covering the accumulated in- and outputs to all processes, was used as the basis for the calculations, and it is thus not possible to quantify and distinguish between the impacts from the single production steps.

Allocation is used to account for co-production of stone wool and 'Grodan', a growing medium used in nurseries. The two products use the same processes and main raw materials, but the recipes differ to a minor extent. Based on the differences of the recipes, the produced amounts and experience from process development, the overall environmental impacts at the production site have been distributed on the two co-products. As the amount of produced Grodan is relatively small compared to the amount of stone wool produced, this approach is not likely to add any significant uncertainty to the results. Likewise, allocation is used to account for the production of stone briquettes produced at the site under investigation, but exported to other production sites.

4.1 Inventory table

For the LCA calculations, the activities can roughly be divided into two main stages, acquisition of raw materials for briquettes and binders, and production of final products. Inventory results for acquisition of briquette and binder raw materials for production of one kilo of stone wool are presented in the CEPMC-format in **Table 2**, together with the total life cycle inventories for stone wool (one kilo and the applied functional unit 1.184 kg). These life cycle inventories thus add up raw materials acquisition, production processes, use of packaging materials and distribution.

Table 2: Inventory table for stone wool

Inventory results		**Unit**	**Briquettes**	**Binder**	**Total per kg stone wool**	**Total per F.U. (1.184 kg)**
Energy	Feedstock, fossil	MJ	0.00	0.83	2.09	**2.47**
	Fossil fuels	MJ	0.56	1.67	11.94	**14.14**
	Primary, fossil (total) (1)	MJ	0.56	2.50	14.03	**16.61**
	Feedstock, renewable	MJ	0.00	0.00	0.75	**0.89**
	Renewable fuels	MJ	0.00	0.09	0.16	**0.18**
	Primary, renewable (total) (2)	MJ	0.00	0.09	0.91	**1.07**
	Electricity (3)	MJ	0.05	0.07	2.59	**3.07**
Total energy consumption (= 1+2+3)		MJ	**0.62**	**2.66**	**17.52**	**20.75**
Resource depletion	Water	g	166	0	3300	**3907**
	Biomass (incl. wood)	g	0	6	35	**42**
	Minerals	g	709	2	777	**920**
	Waste minerals	g	207	0	226	**267**
	Scarce minerals (U as pure Uranium)	g	0.0002	0.0000	0.0040	**0.0047**
	Natural gas	g	1	40	111	**131**
	Oil	g	8	18	65	**77**
	Coal	g	23	1	476	**564**
	Ammonia	g	0	4	4	**5**
Emissions to air	CO_2 (fossil)	g	62	49	1200	**1421**
	CO	g	0.07	0.01	88.98	**105.35**
	SOx	g	0.34	0.16	5.13	**6.08**
	NOx	g	0.28	0.18	2.09	**2.47**
	N_2O	g	0.00	0.00	0.02	**0.02**
	Methane	g	0.21	0.01	0.88	**1.04**
	HCl	g	0.02	0.00	0.05	**0.06**
	HF	g	0.00	0.00	0.01	**0.01**
	H_2S	g	0.00	0.00	0.02	**0.03**
	Ammonia	g	0.00	0.01	2.00	**2.37**
	Hydrocarbons (except CH_4)	g	0.00	0.03	0.18	**0.21**
	VOC	g	0.08	0.10	0.59	**0.70**
	Particulates	g	0.04	0.02	1.01	**1.19**
Emissions to waste water	Suspended solids	g	0.00	0.00	0.02	**0.02**
	BOD	g	0.00	0.00	0.00	**0.00**
	COD	g	0.00	0.02	0.04	**0.05**
	Nitrogenous matter (as N)	g	0.00	0.00	0.01	**0.01**
	Phosphates (as P)	g	0.00	0.00	0.00	**0.00**
Waste (solid)	Hazardous	g	0	0	0	**1**
	Non-hazardous	g	7	0	45	**53**
Total waste		g	**8**	**1**	**46**	**54**

Table 3: Assessment of the contribution to selected environmental impacts from production of 1 kg stone wool and for the functional unit (1.184 kg)

Impact category	Amount per kg	Amount per functional unit	Unit
Global warming	1223	1449	g CO_2-equivalents
Acidification	10.4	12.3	g SO_2-equivalents
Nutrient enrichment CML-method	1.0	1.2	g PO_4^{3-}-equivalents
Nutrient enrichment EDIP-method	10.2	12.0	g NO_3^--equivalents
Photochemical ozone creation	3.9	4.6	g C_2H_4-equivalents
Generation of solid waste	45	53	g non-hazardous waste
Generation of hazardous waste	0.4	0.5	g hazardous waste
Fossil fuels (incl. feedstock)	14.0	16.6	MJ
Renewable fuels (incl. feedstock)	0.9	1.1	MJ
Electricity	2.6	3.1	MJ
Total primary energy consumption	17.5	20.8	MJ
Water consumption	3300	3907	g water

4.2 Impact assessment

Table 3 summarises the quantitative results with respect to global and regional impacts as well as the use of energy resources.

As is strongly indicated in the inventory analysis, the major contribution to all environmental impact categories comes from the final production process and is almost exclusively related to the energy consumption.

4.3 Interpretation

The data for the single stages and activities in the life cycle are considered to be robust and representative for modern stone wool production. The overall impacts are dominated by the production process, with acquisition of raw materials being of minor importance. As the inventory data were based on mass balance calculation, it is not possible to examine the relative importance of the single production steps in more detail.

It is noted that, in general, there will be differences in the energy sources used at specific production facilities. In an earlier study of stone wool production in the U.K. [5], less electricity (factor 2) and more fossil fuels (25%) were used in the production, compared to the Danish production site. Obviously, such differences are also reflected in the inventory and impact assessment results. In the two studies, the emission of CO_2 is almost the same, while the emission of SO_2 and NO_x in the present study is 70% and 50%, respectively, of those reported in the U.K. study. Such differences may be due to differences in the basic energy conversion inventories used in the two studies, but may also mirror actual technological differences, e.g. with respect to flue gas cleaning.

The potential for improvement relating to recycling of post-consumer waste in the production process is indicated by the environmental impacts associated with production of briquettes. Post-consumer waste is only utilised to a very limited extent in current production, but the amount may increase significantly due to take-back schemes, either voluntary or forced by regulatory demands. The environmental benefits from recycling appear to be small in the examined impact categories, e.g. a maximum reduction potential of 0.67 MJ/kg. Other types of impacts not addressed in the study could also be important in relation to recycling, e.g. avoidance of landscape degradation from stone quarries. The transportation picture will also change significantly, i.e. transport of stone materials by ship and truck will be reduced at the expense of an increase in land transportation of stone wool insulation waste from demolished buildings. Whether this change will provide a real benefit for the environment is questionable.

5 Results for Paper Wool

Paper wool has been known as an insulation material since the end of the 19th century, however, an industrial production was only started in the USA after 1945. In Europe an industrial production has been known since 1974, and today, paper wool is produced in England, France, Germany, Sweden, Denmark, Finland and Poland. Paper wool can be installed as a dry material or sprayed into an existing construction in a wet condition, depending on the application.

The basic raw material for paper wool is old newsprint that is shredded in an auto- or hammer-mill, concomitantly adding flame-retardants and biocides. The finished product is stored in containers before being blown into cavities. Fig. 2 shows a simplified overview of the combined life cycles of newsprint, newspapers and paper wool. The figure indicates that old newsprint leaving the paper cycle, either as waste (landfill or incineration) or for other products like insulation materials, must be replaced by a corresponding amount of virgin fibers. When old newsprint is recycled to 'new' newsprint, some of the fibers are discarded as waste because they do not have the necessary technical properties, e.g. by being too short. On average, one seventh of the fibers ends up as waste in conventional recycling of old newsprint and must therefore be replaced by virgin fibers in order to produce the volume of newsprint in demand. As a consequence of these considerations, it has been assumed in the inventory calculations that 6/7 of the old newsprint is made from virgin pulp and the remaining 1/7 is made up of avoided waste. Thus, the initial newsprint paper cycle, i.e. production, use and disposal of newspapers, is not included in the calculations.

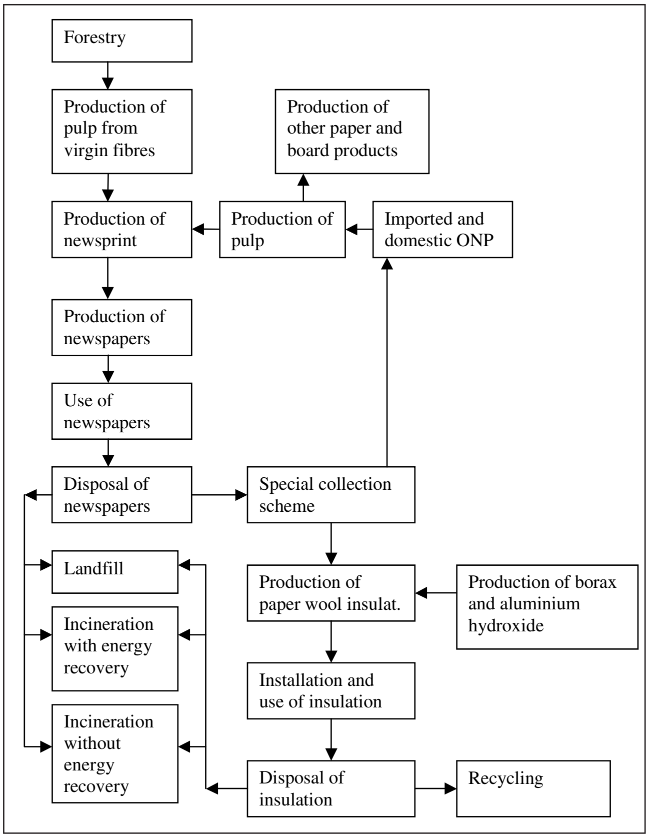

Fig. 2: A simplified overview of the combined life cycles of newsprint, newspapers and paper wool

In general, newsprint is produced from a mixture of virgin pulp and pulp based on recycled fibers from old newsprint. The proportion of these two materials may vary considerably from one company (or country) to the other, but it is always necessary to use a certain amount of virgin fibers in order to ensure the technical properties of the product, e.g. the strength of the paper. As such it can be regarded as a waste material originally being based on a renewable resource. However, today's paper market is global, and old newsprint is a valuable raw material that is an integral part of the paper industry.

The market for pulp and paper has been increasing for a very long period and it is not anticipated to stagnate or decrease in the near future. In Europe, the Swedish and Finnish pulp and paper industries are the main exporters of virgin paper and pulp to other European countries. At the same time, Sweden is a net importer of recovered paper, whereas Finland is a net exporter, although only in small quantities. Finland is thus one of the few countries where newsprint production is based solely on virgin materials at some production facilities.

The amount of paper that is recovered will increase until at least 2005. It is anticipated that the pulp and paper industry will be able to utilise all of the collected paper. It is therefore assumed that by using recovered paper for purposes other than recycled paper products, it is necessary to increase the amount of virgin raw materials in the pulp and paper industry in order to satisfy the expected increase in demand. It seems reasonable to assume that producers in most countries will be affected (will increase production on existing plants and/or install new capacity), rather than just a few selected key players on the market. Accordingly, the paper addresses the environmental impacts that are observed, when parts of the waste paper stream are diverted from production of recovered paper to production of paper wool insulation.

The system expansion approach is used in the assessment of paper wool insulation, where it is assumed that the raw material, old newsprint, draws from the same pool of resources as production of newsprint, i.e. newspapers collected in special schemes. It is therefore assumed in the calculations that every kilo of old newsprint leaving the system (in this case for production of insulation materials) must be replaced by a corresponding amount of virgin fibers. There is thus no need for allocation of the impacts from production of the initial newsprint.

5.1 Inventory results

In the case of production of thermo-mechanical pulp, market analysis point to Sweden and Finland as the main future suppliers in Western Europe. The Swedish Forest Association was not able to provide the requested information, because the Swedish production of newsprint is always done in integrated mills where old newsprint is one of the raw materials. Finnish LCA data for 'typical' production of virgin thermo-mechanical pulp obtained from the Finnish Pulp and Paper Research Institute KCL (Newsprint production. Reference code DEF-10719) was used. These inventory data include harvesting operations, sawmill process, transport of wood and newsprint production at the production facility (wood handling, mechanical pulping, paper machine and activated sludge plant). The data are of high quality, but relate specifically to Finnish production, which may differ from Swedish production in some ways, e.g. relating to the energy scenario. As the KCL data were the only source, it is not possible to describe or quantify the potential differences further. In a sensitivity analysis, data for Swiss production of ground wood pulp [13] were applied as a substitute for the Finnish data. This gives an indication of the potential ranges of environmental impacts, however, the data are somewhat older and it is questionable whether they are fully representative for today's technology.

The KCL inventory also specified consumption of the papermaking chemicals, i.e. sodium hydroxide (NaOH), hydrogen peroxide (H_2O_2), sodium silicate (Na_2SiO_3), and EDTA. Information regarding EDTA production could not be disclosed by KCL for confidentiality reasons, and this element was therefore excluded from the inventory calculations. Data for production of sodium hydroxide and hydrogen peroxide more recent than the KCL data were obtained from literature sources [12,18] and used.

The second raw material in paper wool production – 'avoided waste' – is also addressed by using Finnish information from the KCL database (Reference code KCL-10532-10738). The raw materials for the process are newspaper (60%), LWC-paper (lightweight coated paper) (30%) and advertisements (10%). The process involves de-inking (defibering and flotation), bleaching, active sludge treatment and heat production from sludge incineration. The data are from 1996, and the technological level is the European average from the same year. In addition to the main chemicals used for production of newsprint, unspecified additives (2.4 g/kg), sodium dithionite ($Na_2S_2O_4$; 0.3 g/kg), fatty acids (5.8 g/kg) and talc (9.5 g/kg) are used in the process. Due to lack of inventory data, the latter chemicals have not been included in the inventory. Due to their relatively small amount, less than 2% of the total input, this omission is assumed to be of minor importance in the overall results.

At the paper wool factory, paper is received in loose weight or in bales. Paper in bales is first shredded in an auto-mill and continues then through a hammer-mill where it is further shredded and flattened together with paper received in loose weight. At the same time, flame-retardants and biocides (borax, boric acid, and aluminium hydroxide) are added in amounts of 3, 3, and 9%, respectively. Data for borax and boric acid was obtained from Borax Rio Tinto [19,20] and for aluminium hydroxide from the Swiss BUWAL 232 report [14]. The energy consumption in the process is modest: 0.42 MJ/kg of electricity and 0.404 MJ/kg of natural gas [6].

The final product is packed in polyethylene bags, containing about 25 kg. The consumption of LDPE has been calculated as 7.2 g/kg [6].

The inventory results for paper wool are presented in **Table 4**.

From additional calculations it is deduced that the main consumption of raw materials and energy as well as emissions to all compartments are found in the raw material pro-

Table 4: Inventory results for 1 kg paper wool and for the functional unit, 1.280 kg

Inventory results		Unit	Per kg	Per functional unit (1.280 kg)
Energy	Feedstock, fossil	MJ	0.33	0.43
	Fossil fuels	MJ	4.94	6.32
	Primary, fossil (total)	MJ	5.28	6.75
	Feedstock, renewable	MJ	10.93	13.99
	Renewable fuels	MJ	1.06	1.36
	Primary, renewable (total)	MJ	11.99	15.35
	Electricity	MJ	3.24	4.14
Total energy consumption		MJ	**20.50**	**26.24**
Resource depletion	Water	g	642	822
	Biomass (incl. wood)	g	984	1259
	Minerals	g	160	205
	Waste minerals	g	0	0
	Scarce minerals (U as pure Uranium)	g	0.0014	0.0018
	Natural gas	g	48	61
	Oil	g	83	106
	Coal	g	79	101
	Ammonia	g	0	0
Emissions to air	CO_2 (fossil)	g	629	805
	CO	g	0.88	1
	SO_x	g	2.25	2.88
	NO_x	g	2.92	3.74
	N_2O	g	0.00	0.01
	Methane	g	0.44	0.57
	HCl	g	0.00	0.00
	HF	g	0.00	0.00
	H_2S	g	0.00	0.00
	Ammonia	g	0.00	0.00
	Hydrocarbons (except CH_4)	g	0.96	1.22
	VOC	g	0.31	0.39
	Particulates	g	3.97	5.08
Emissions to waste water	Suspended solids	g	0.64	0.82
	BOD	g	0.65	0.84
	COD	g	5.21	6.66
	Nitrogenous matter (as N)	g	0.07	0.09
	Phosphates (as P)	g	0.00	0.00
Waste (solid)	Hazardous	g	1.3	1.7
	Non-hazardous	g	24	30
	Total waste	g	**25**	**32**

duction phase, accounting in general for more than 95% of the environmental interventions. The paper wool production process itself does not contribute significantly, simply because the process (shredding of paper, blending with chemicals) is rather undemanding in terms of energy consumption and does not release significant emissions of potentially hazardous substances to the environment.

5.2 Impact assessment

The results of the impact assessment of the basic scenario as well as the range of sensitivity analysis performed are given in **Table 5**.

It is worth noting that the consumption of fossil fuels and electricity accounts for about 40% of the overall energy consumption. Despite perceptions to the contrary, paper wool is not a wholly renewable material. As for most other products made from renewable materials, a certain amount of fossil fuels is needed in their production and transportation. As a consequence, paper wool contributes significantly to the conventional energy-related impacts such as global warming and acidification.

Production of newsprint is not surprisingly the most demanding activity with respect to consumption of energy resources, especially fossil fuels, electricity and renewable feedstock (wood). According to the information in the inventory from KCL, about 4 MJ/kg of different fossil fuels are consumed along with 3.8 MJ of electricity per kilo of newsprint produced from virgin fibers. When adding the feedstock energy in the newsprint (15 MJ/kg), this constitutes more than 90% of the overall energy consumption.

5.3 Interpretation

In the inventory description, the waste disposal scenarios were subject to a sensitivity analysis. Re-use is not considered as a viable option, whereas partial landfilling and incineration (20% landfilling or incineration; 80% recycling in low grade applications) are seen as the most probable options also in the future. Additionally, the importance of using other data sources for paper production was investigated. A commonly used source is the Swiss BUWAL 250 Report [13] that contains inventory information on a number of different pulp and paper qualities according to Swiss conditions. For simplification, it was chosen to replace the process of 'Newsprint production' (based on Finnish data) with 'Production of ground wood pulp', based on the BUWAL 250 report [13]. Obviously, the Swiss data represent a somewhat different process/product (pulp with 90% dry matter instead of finished newsprint) and can therefore be assumed to give an underestimation of the environmental impacts, e.g. because drying of the paper is not included to the same extent.

The sensitivity analysis shows that incineration with energy recovery is preferable from an environmental point of view, at least with the system boundaries for waste treatment used in the study. When incinerated, the inherent energy in paper wool is utilized, replacing fossil fuels for production of district heating and electricity. This has a positive influence on the overall energy consumption (mostly consumption of fossil fuels) as well as the contribution to global warming. The beneficial effects are counterbalanced to a very minor extent by small increases in the contribution to nutrient enrichment and photochemical ozone creation.

The sensitivity analysis also shows that landfilling has a detrimental influence on the global warming potential and the generation of non-hazardous waste. The increase in global warming potential is based on the assumption that the paper wool will degrade in the landfill, emitting significant amounts of methane with a high global warming potential.

When using Swiss data instead of Finnish, the most significant change is a large increase in consumption of electricity (by a factor 3) and, accordingly, also in total energy consumption (about 35%). The contribution to photochemical

Table 5: Impact assessment results for paper wool (functional unit = 1.28 kg) in the base case scenario as well as the scenarios investigated in the sensitivity analyses

Impact category	Unit	Paper wool – 100% recycling in low grade applications (base case scenario)	Paper wool – 20% incinerated – 80% recycled	Paper wool – 20% landfilled. 80% recycled	Paper wool – BUWAL data – 100% recycling in low grade applications
Global warming	g CO_2-equivalents	819	645	2221	709
Acidification	g SO_2-equivalents	5.5	5.5	5.5	7.7
Nutrient enrichment CML-method	g $PO4^{3-}$-equivalents	0.7	0.7	0.7	0.5
Nutrient enrichment EDIP-method	g $NO3^{-}$-equivalents	5.5	5.6	5.4	4.6
Photochemical ozone creation	g C_2H_4-equivalents	0.2	0.3	0.2	0.6
Generation of solid waste	g non-hazardous waste	30	30	286	30
Generation of hazardous waste	g hazardous waste	1.7	1.6	1.6	0.8
Fossil fuels (incl. feedstock)	MJ	6.8	4.6	6.7	6.6
Renewable fuels	MJ	15.4	15.4	15.4	17.8
Electricity	MJ	4.1	4.0	4.1	11.9
Total energy consumption	MJ	26.2	24.0	26.2	36.3
Water consumption	g water	822	822	822	70

ozone formation increases by more than a factor 2, and the acidification potential increases by about 25%. The nutrient enrichment potential decreases by 15–20% and the generation of hazardous waste decreases by a factor 2. No efforts have been devoted to explain the differences in any detail. There is little doubt that the electricity scenarios in the two countries play an important role, but this cannot explain all the differences.

Overall, it is concluded that the differences found are not of a magnitude that changes the results of the comparison between the three product systems significantly. The differences, however, underline that in order to get a very precise view of the environmental impacts from different paper products, it is necessary to look at the specific conditions in the actual geographical area. The importance is not very large in the present case, but for other types of products the choice of geographical boundaries can be crucial.

6 Flax

Traditionally, flax has been grown to mainly yield either oil seeds (linseed) or fibers, but dual purpose crops are now being cultivated, from which, after combining, the dry straw is mechanically processed to produce relatively short fibers which may be used in the manufacture of specialist papers, composite materials, and biodegradable matting products [21].

Flax is currently being redeployed for industrial use in Europe. Only small amounts of fiber flax are being produced, and, at the same time, different climatic and agricultural conditions in Europe cause large variations in the yield from one year to another and from one country/region to another. The inventory for flax production is therefore based on average conditions in Europe, using a weighted average for the yield over a five-year period in European countries.

The basic raw material for flax insulation is flax fibers. After harvesting, the flax plants are husked and the fibers separated out for further processing. The fibers are mixed with heated polyester binder (15% w/w) to add strength and rigidity, and flame-retardants (10% w/w) are sprayed upon the thin layers of mixed fibers to fulfil regulatory requirements. The layers are folded and cut into mats of the desired size. The activities in the life cycle of flax insulation products are shown in overview in **Fig. 3**.

Flax insulation products are still in a development phase and, accordingly, different products can be found on the European market. The main difference is probably the composition of the final insulation product, where the amount and type of binder material vary significantly. An Austrian product has been chosen for the comparisons, because it fulfils the legal requirements regarding fitness for use and, at the same time, is among the most visible products on the market. A Danish product is also examined, although it does not have the required flame retardant properties. It is, however, included in the sensitivity analysis because it gives an indication of the potential for reduction in environmental impacts, e.g. through a reduction in the content of polyester binder.

The environmental impacts from production of polyester binder (15% w/w) and borax (1% w/w) were included by using data from recent inventories by APME [10] and Rio Tinto [19], respectively. The impacts from diammonium hydrogen phosphate (9% w/w) were included by using older (1996) confidential inventory data from a Norwegian producer.

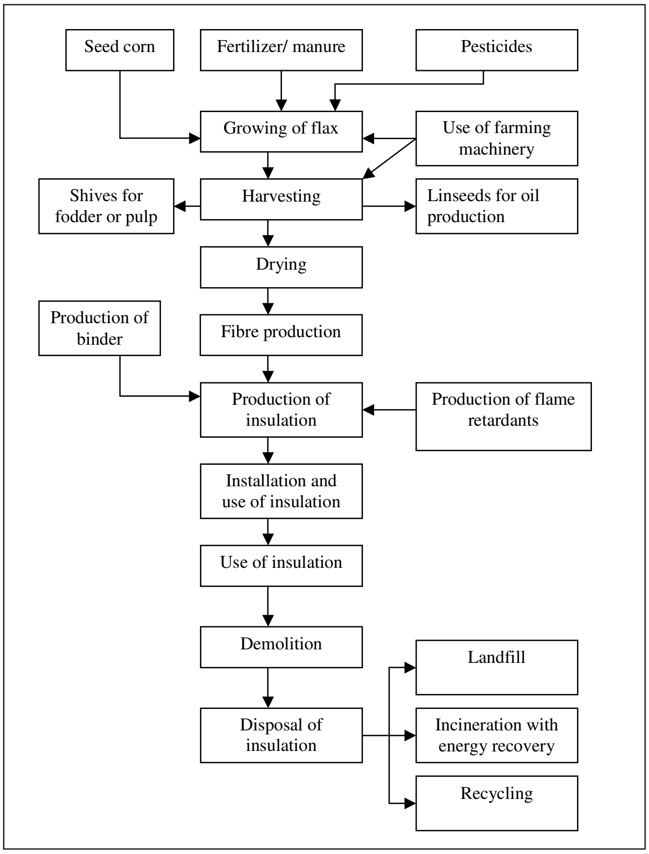

Fig. 3: Flow diagram for flax

System expansion is used to calculate the impacts from flax growing. Here it has been assumed that the co-product from fiber production, flax oil seeds, replaces flax oil seeds produced by using a different species of seeds that give a higher yield of oil, but no fibers that are suitable for industrial production. Furthermore, it is assumed that the shives from flax fiber production are used as cattle fodder and the flax system is therefore expanded to also include this. As the expansion of the flax system is based on a limited amount of information, an economic allocation is used in the sensitivity analysis in order to investigate the importance of using system expansion or allocation in flax growing.

LCA of agricultural products poses several methodological problems, especially if an attempt is made to generalise the results to a large geographical area like the EU, as is the case in the current study. Input of fertilisers and pesticides vary with local and regional soil conditions, and the yield differs significantly between regions and from year to year, depending primarily on climatic conditions (precipitation, temperature). Data collection is furthermore complicated by fiber flax being a new and minor crop in the EU with only scattered information relating to agricultural practices being available for LCA calculations.

Table 6: Flax production data

Parameter	Value
Inputs – flax growing	
Input of seeds	80 kg/ha
Input of fertilizer	Nitrogen: 40 kg/ha Phosphorous: 17 kg/ha Potassium: 70 kg/ha
Input of pesticides	0.174 kg/ha
Energy – Machinery production	3053 MJ/ha (diesel)
Energy – Agricultural activities	3500 MJ/ha
Outputs – flax growing	
Yield of flax straw	5.55 t/ha
Yield of flax fiber for insulation	1.36 t/ha
Yield of shives	4.19 t/ha
Yield of seeds	1.3 t/ha
Drying of flax fibers	40 kWh/ton flax straw
Production of flax insulation	
Flax fibers	750 kg/t
Polyester binder	150 kg/t
Borax	10 kg/t
Diammonium hydrogen phosphate	90 kg/t
Electricity	3.6 GJ/t
Natural gas	7.2 MJ/t
HDPE packaging	1 kg/t

In the study, a general picture was drawn by using European averages where applicable, e.g. in relation to yield of flax fibers and seeds, in combination with specific information about flax growing (e.g. Danish fertiliser recommendations) and production of flax insulation products. Thus, each part of the information used has an inherent uncertainty, which is described in more detail in the report. **Table 6** shows the flax production data used in the calculation of the basic scenario.
The inventory results for one kilo of flax insulation as well as for the functional unit (1.26 kg) are shown in **Table 7**.

With three outputs from flax growing, fibers (for insulation), seeds (with an oil content) and shives (for animal fodder), the problem of co-product allocation emerges. The ISO LCA Standards prescribes that allocation should be avoided, where possible. In the present study, system expansion was used to account for the environmental impacts from fiber production. This was done by assuming that the oil that can be utilised from fiber flax replaces linseed oil (produced from oil flax) and shives replace grass for animal fodder. The impacts from production of equivalent amounts of oil seeds and grass in weight units were subtracted from the overall impacts from fiber flax production to give figures for the

Table 7: Inventory results for flax insulation for 1 kg as well as for the functional unit (1.26 kg). Base case scenario, i.e. 100% is recycled in road construction or similar low-grade recycling)

Inventory results		Unit	Per kg	Per functional unit (1.260 kg)
Energy	Feedstock, fossil	MJ	5.97	7.53
	Fossil fuels	MJ	16.12	20.31
	Primary, fossil (total)	MJ	22.09	27.84
	Feedstock, renewable	MJ	12.15	15.31
	Renewable fuels	MJ	0.00	0.00
	Primary, renewable (total)	MJ	12.15	15.31
	Electricity	MJ	5.23	6.58
Total energy consumption		MJ	**39.47**	**49.73**
Resource depletion	Water	g	4580	5771
	Biomass (incl. wood)	g	750	945
	Minerals	g	167	210
	Waste minerals	g	0	0
	Scarce minerals (U as pure Uranium)	g	0.01	0.01
	Natural gas	g	271	341
	Oil	g	233	293
	Coal	g	374	471
	Ammonia	g	0	0
Emissions to air	CO_2 (fossil)	g	1700	2142
	CO	g	1.46	2
	SO_x	g	9.18	11.57
	NO_x	g	5.90	7.44
	N_2O	g	0.33	0.41
	Methane	g	3.32	4.19
	HCl	g	0.03	0.04
	HF	g	0.00	0.00
	H_2S	g	0.00	0.00
	Ammonia	g	0.01	0.02
	Hydrocarbons (except CH4)	g	1.75	2.20
	VOC	g	0.67	0.85
	Particulates	g	1.22	1.54
Emissions to waste water	Suspended solids	g	0.07	0.09
	BOD	g	0.15	0.19
	COD	g	0.29	0.37
	Nitrogenous matter (as N)	g	0.44	0.56
	Phosphates (as P)	g	0.00	0.00
Waste (solid)	Hazardous	g	0.3	0.4
	Non-hazardous	g	97	122
Total waste		g	**97**	**123**

Table 8: Results of impact assessment and sensitivity analysis for flax. All impacts calculated per functional unit (1.26 kg)

Impact category	Unit	Flax – 100% recycling in low grade applications 'Base Case'	Flax – 20% incinerated – 80% recycled	Flax – 20% landfilled – 80% recycled	Flax – 20% composting – 80% recycling	Flax – economic allocation	Flax – Danish production
Global warming	g CO_2-equivalents	2357	2310	3384	2369	2899	888
Acidification	g SO_2-equivalents	16.8	17.1	16.8	16.8	20.9	5.1
Nutrient enrichment CML-method	g PO_4^{3-}-equivalents	1.2	1.3	1.2	1.2	2.3	0.7
Nutrient enrichment EDIP-method	g NO_3^--equivalents	12.6	13.3	12.6	12.6	23.6	7.4
Photochemical ozone creation	g C_2H_4-equivalents	0.5	0.6	0.5	0.5	0.9	0.3
Generation of solid waste	g non-hazardous waste	122	122	437	122	121	37
Generation of hazardous waste	g hazardous waste	0.4	0.4	0.4	0.4	0	0.2
Energy consumption Fossil fuels (incl. feedstock)	MJ	27.8	25.8	27.8	27.8	31.7	9.8
Energy consumption Renewable fuels	MJ	15.3	15.3	15.3	15.3	15.3	19.4
Electricity	MJ	6.6	6.5	6.6	6.7	6.5	2.2
Total primary energy consumption	MJ	49.7	47.6	49.7	49.8	53.6	31.4
Water consumption	g water	5771	5771	5771	5771	5771	3856

impacts from production of flax fibers alone. As a part of the sensitivity analysis, an economic allocation between the co-products was also performed. Here, market prices including subsidies for fibers, seeds and grass were used to distribute the environmental impacts on the co-products. Both approaches are associated with a relatively high uncertainty because of bad or missing data, but as the agricultural processes only play a minor role in the overall assessment, no extensive data collection on agricultural practices and market conditions was performed.

6.1 Impact assessment

Table 8 presents the results of the impact assessment of the base case scenario for flax as well as the range of sensitivity analysis performed on various waste options (incineration, landfill and recycling).

6.2 Interpretation

The base case has been supplemented with a number of different scenarios, indicating the importance of waste disposal, economic allocation vs. system expansion, and future product development. The results indicate that the best disposal method is incineration with energy recovery. With 20% being incinerated following its useful life, about 8% of the overall consumption of fossil fuel can be avoided without significant changes in the impact categories examined. Landfilling is the worst option, leading to an increase in the global warming potential because some of the flax degrades anaerobically to methane instead of carbon dioxide. When composted, the impacts examined are very similar to those from recycling in low-grade applications. This is not surprising as the fate of the material over a 100-year period is assumed to be same. Thus, the main difference between the two disposal methods is the usability of the product following treatment. Re-use has not been examined in any detail. It can only be recommended if it can be ensured that the fitness for use is the same as for virgin products. If the insulating properties are reduced by just a few percent, the lifetime energy savings are reduced far more than the cost of producing virgin insulation material.

If economic allocation is applied instead of system expansion, a general increase in environmental impacts is observed, ranging from about 8% increase in energy consumption to a factor 2 for photochemical ozone formation. Both approaches are associated with a relatively high degree of uncertainty, and the differences between the results are primarily seen as an illustration of the variance of the agricultural system examined.

The improvement possibilities by further product development is shown by the differences between the base case product with a high content of binder and flame retardant and an alternative product with less binder and flame retardant. Such a product is currently in the final stages of development. The alternative product consumes only 65% of the energy in the base case product and has a reduced impact in the categories examined of between 40% and a factor 3. The products are not comparable with respect to their fitness for use (the alternative product cannot be approved for building insulation with its current properties), but the results indicate that there is a large improvement potential for flax insulation.

It is concluded that the base case scenario chosen for flax insulation is neither best nor worst case but can be regarded as reasonably representative of current practise. There are large variations in the scenarios examined. Some of these can be attributed to actual differences in life cycle impacts, whereas others give an indication of the inherent uncertainties in LCA of agricultural products. These uncertainties must be addressed as an integral part of the comparison of different insulation products.

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Part 2 'Comparative Assessment' summarises the results of a comparative LCA study of HT stone wool, flax representing crop grown products, and paper wool representing recycled products applied for roof insulation, in which an attempt is made to answer the question of whether the biological products flax and paper wool are more environmentally preferable than the mineral product stone wool representing more traditional insulation materials. Of the three products compared, paper wool has in general the lowest global and regional environmental impacts and flax insulation the highest, with stone wool falling in between. A notable exception is the total energy use, where stone wool has the lowest consumption, followed by cellulose and flax. The study also addresses occupational health, using an approach similar to that used for risk assessment. Here, the modern less biopersistent stone wool products are seen as the safest alternatives, because of a low potential for exposure, sufficient animal testing and the absence of carcinogenic properties. Overall, the differences between the investigated products are of minor environmental significance compared to that achieved by their use namely insulation of buildings, which saves energy corresponding to more than 100 times the environmental impacts incurred in their manufacture. The main conclusion is that the quality and fitness for use of an insulation product throughout its useful life span is the most important aspect in the life cycle of insulation materials.

LCA Case Studies

A Comparative Life Cycle Assessment of Building Insulation Products made of Stone Wool, Paper Wool and Flax

Part 2: Comparative Assessment

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Preamble. Insulation of buildings is an important technology for saving heating energy and for a sustainable development. The results of a comparative LCA study of three insulation products applied for roof insulation are summarised in two parts. The products selected are based on HT stone wool representing traditional products - flax representing crop grown products and paper wool representing recycled products, respectively. Although the three materials have vastly different life cycles, they yet fulfil the same function; the methodology used should be of general interest.

Part 1 of the paper contains the project background, the goal and scope definition and three life cycle assessments for the three individual products, with a detailed inventory analysis, impact assessment, sensitivity analysis and interpretation. The actual comparison of the results from the three individual life cycle assessments is presented in **Part 2.** An attempt is made to answer the question of whether the biological products flax and paper wool are more environmentally preferable than the mineral product stone wool representing more traditional insulation materials.

In general, paper wool has the lowest global and regional environmental impacts, and flax insulation the highest, with stone wool falling in between. A notable exception is the total energy use, where stone wool has the lowest consumption followed by cellulose and flax. The study also addresses occupational health issues using an approach similar to that for risk assessment. Here, the less biopersistent HT stone wool products are seen to be the safest alternatives, because of a low potential for exposure, sufficient animal testing, and the obvious absence of carcinogenic properties.

It must be recognised that insulation of buildings saves more than 100 times the environmental impacts associated with the production and disposal of the products used for insulation. Compared to that and the inherent uncertainties in the LCA, the differences between the investigated products are of minor environmental significance. Therefore, the main conclusion demonstrated in the study is that the quality and fitness of an insulation product is the most important aspect in the life cycle of insulation materials.

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Abstract

Part 2 summarises the results of a comparative LCA study of HT stone wool, flax representing crop grown products and paper wool representing recycled products applied for roof insulation, in which an attempt is made to answer the question of whether the biological products flax and paper wool are more environmentally preferable than the mineral product stone wool representing more traditional insulation materials. Of the three products compared, paper wool has, in general, the lowest global and regional environmental impacts and flax insulation the highest, with stone wool falling in between. A notable exception is the total energy use, where stone wool has the lowest consumption, followed by cellulose and flax. The study also addresses occupational health, using an approach similar to that used for risk assessment. Here, the modern less biopersistent stone wool products are seen as the safest alternatives, because of a low potential for exposure, sufficient animal testing and the absence of carcinogenic properties. Overall, the differences between the investigated products are of minor environmental significance compared to that achieved by their use, namely insulation of buildings, which saves energy corresponding to more than 100 times the environmental impacts incurred in their manufacture. The main conclusion is that the quality and fitness for use of an insulation product throughout its useful life span is the most important aspect in the life cycle of insulation materials.

Keywords: Building insulation; case study; comparative LCA; flax; paper wool; stone wool

1 Introduction

The comparison between the three insulation systems is based on both the inventory results and the impact assessment. The main focus is on the impact assessment results, but the inventories provide more detail, especially with respect to the consumption of energy and fuels. Information from intermediate calculations, not shown in the paper, are used in some cases to provide even more detail with respect to the basic cause of the impacts and to give information of the sensitivity of the choices made throughout the study.

2 Comparison of Inventory Results

It is emphasized that the comparisons made between systems are based on inventories that have been established in very different ways. The stone wool inventory is mainly based on information from one production site, using a technology that is assumed to be representative for most other production sites. The inventory for flax insulation is a combination of average considerations and information from one producer, the representativity of which could not be established. The inventory for paper wool is based on a typical production process for newsprint in one country, combined with a representative recipe for the final product. Thus, the comparison considers three representative products, but especially for flax and paper wool insulation there may be appreciable differences to products made in other countries or with different technologies.

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The inventory results of the three different insulation products used to fulfil the same functional unit are summarised in **Table 1**.

3 Comparison of Impact Assessment Results

The life cycle impacts of the three different insulation products used to fulfil the same functional unit are summarised in **Table 2**.

Table 1: Life cycle inventory results per functional unit for the three insulation systems

Inventory results per functional unit		Unit	Stone wool	Flax	Paper wool
Energy	Feedstock, fossil	MJ	2.47	7.53	0.43
	Fossil fuels	MJ	14.14	20.31	6.32
	Primary, fossil (total)	MJ	16.61	27.84	6.75
	Feedstock, renewable	MJ	0.89	15.31	13.99
	Renewable fuels	MJ	0.18	0.00	1.36
	Primary, renewable (total)	MJ	1.07	15.31	15.35
	Electricity	MJ	3.07	6.58	4.14
Total energy consumption		MJ	**20.75**	**49.73**	**26.24**
Resource depletion	Water	g	3907	5771	822
	Biomass (incl. wood)	g	42	945	1259
	Minerals	g	920	210	205
	Waste minerals	g	267	0	0
	Scarce minerals (U as pure Uranium)	g	0	0	0
	Natural gas	g	131	341	61
	Oil	g	77	293	106
	Coal	g	564	471	101
	Ammonia	g	5	0	0
Emissions to air	CO_2 (fossil)	g	1421	2142	805
	CO	g	105	2	1
	SOx	g	6.08	11.57	2.88
	NOx	g	2.47	7.44	3.74
	N_2O	g	0.02	0.41	0.01
	Methane	g	1.04	4.19	0.57
	HCl	g	0.06	0.04	0.00
	HF	g	0.01	0.00	0.00
	H_2S	g	0.03	0.00	0.00
	Ammonia	g	2.37	0.02	0.00
	Hydrocarbons (except CH_4)	g	0.21	2.20	1.22
	VOC	g	0.70	0.85	0.39
	Particulates	g	1.19	1.54	5.08
Emissions to waste water	Suspended solids	g	0.02	0.09	0.82
	BOD	g	0.00	0.19	0.84
	COD	g	0.05	0.37	6.66
	Nitrogenous matter (as N)	g	0.01	0.56	0.09
	Phosphates (as P)	g	0.00	0.00	0.00
Waste (solid)	Hazardous	g	0.5	0.4	1.7
	Non-hazardous	g	53	122	30
	Total waste	g	**54**	**123**	**32**

Table 2: Life cycle impacts for three different insulation materials used to fulfil the same functional unit

Impact category	Unit	Stone wool	Flax	Paper wool
Global warming	g CO_2-equivalents	1449	2357	819
Acidification	g SO_2-equivalents	12.3	17	5.5
Nutrient enrichment CML-method	g PO_4^{3-}-equivalents	1.16	1.22	0.7
Nutrient enrichment EDIP-method	g NO_3^--equivalents	12.0	12.6	5.5
Photochemical ozone creation	g C_2H_4-equivalents	4.6	0.5	0.2
Generation of solid waste	g non-hazardous waste	53	122	30
Generation of hazardous waste	g hazardous waste	0.5	0.4	1.7
Fossil fuels (incl. feedstock)	MJ	16.6	27.8	6.8
Renewable fuels (incl. feedstock)	MJ	1.1	15.3	15.4
Electricity	MJ	3.1	6.6	4.1
Total energy consumption	MJ	20.6	49.7	26.2
Water consumption	g water	3907	5771	822

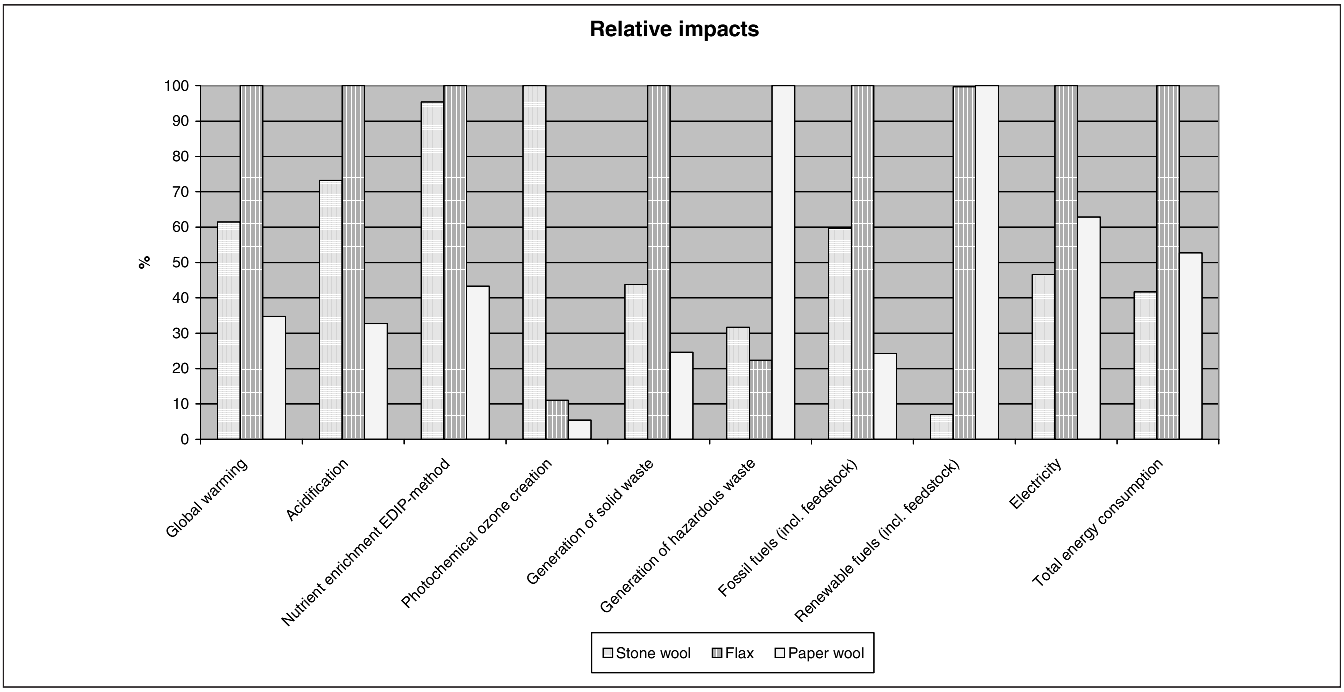

Fig. 1: Comparison of the contribution to different impact categories

As can be seen from the tables, the comparative picture is somewhat heterogeneous, and each of the impact parameters is therefore discussed in the following sections.

The contribution to different environmental impacts from the three very different insulation systems is illustrated in **Fig. 1**.

3.1 Global warming

The contribution to global warming differs by almost a factor 3 between the least contributing material (paper wool) and the most contributing (flax). It may be surprising that flax insulation, which in principle is based on a renewable resource, has the largest contribution. There are, however, a number of reasons for this. Growing of flax requires, like most other agricultural products, artificial fertilizers in order to give an economically sustainable yield. Production of fertilizers is relatively energy intensive, causing emissions of carbon dioxide. In the production, emissions of dinitrogen oxide (N_2O) occur and with N_2O being a strong greenhouse gas, the contribution from fertilizer production becomes significant.

Furthermore, a fraction (1%) of the nitrogen compounds spread on the soil as fertilizer is assumed to transform and evaporate from the fields as N_2O, also contributing significantly in the overall result. The binder and flame retarding materials used to give the final products the desired technical properties use relatively large amounts of fossil fuels for their production. Emissions of carbon dioxide and methane from the combustion processes also contribute to the overall results.

Finally, the production process itself also contributes through emissions from its energy consumption. The energy is used to melt the binder materials before mixing with the flax raw material, but it is also assumed that some of the energy consumption is used for overhead, e.g. lighting and space heating.

The main contribution for stone wool insulation comes from the production process where fossil fuels are used for melting and production of energy. Production of stone raw materials is not very demanding in terms of energy consumption and there are no other emissions during their production that have a global warming potential. Binder materials are only used in small amounts and, besides emissions from energy consumption, there are no other known emissions that contribute to global warming in significant amounts.

Paper wool performs best with respect to global warming potential. Although the raw material for paper wool, old newsprint, primarily is based on renewable resources, its production still demands an input of fossil fuels and, accordingly, also causes emissions of carbon dioxide, which is the main contributor (more than 55%) in this system. Other significant sources are production of aluminium hydroxide and the final production, each contributing with 10–15%.

3.2 Acidification

The same picture is seen for acidification potential as for global warming potential, i.e. that flax insulation has the highest impact potential, and that it is about factor 3 higher than for paper wool and 40% higher than for stone wool. The main contribution in the flax system comes from production of binder and flame-retardants, constituting about 50% of the overall contribution. The production process contributes about 30%, while the impacts from flax growing contribute about 6%. The remaining contributions are distributed across a large number of processes and can be attributed to emissions of sulfur dioxide and nitrogen oxides from the combustion processes.

The main contribution in the stone wool system comes – not surprisingly – from the production process and is almost solely related to emissions of sulfur dioxide and nitrogen oxides from combustion of fossil fuels. It is not possible to distinguish between different production steps.

In the paper wool system, newsprint production contributes with about 35%, production of flame-retardants and biocides (especially aluminium hydroxide) with about 15%. Other significant contributions are the final production process (about 8%), and transportation by boat and truck of the newsprint from Finland to Central Europe (about 9%). The reason for the latter is that it is assumed that the boat transporting the newsprint is diesel powered with a fuel of a relatively high content (3%) of sulfur and having no emission control equipment. This may give an overestimation of the contribution to acidification, especially since it is uncertain whether emissions from boats at sea will reach areas where they may have an adverse effect.

3.3 Nutrient enrichment

There is some uncertainty associated with the assessment of the contribution to nutrient enrichment (eutrophication, nutrification), primarily because the inventory data are often of rather poor quality with respect to waterborne emissions of nitrogen and phosphorous containing compounds. The main conclusion, i.e. that the nutrient enrichment potential of the flax and stone wool systems are very similar while the contribution from the paper wool system is about half of that of the other two systems, should therefore be regarded cautiously.

The contribution from leaching of nitrogen in the flax system has not been included in the calculations due to lack of data. The importance of this is relatively small if system expansion is used, since similar emissions of nitrogen can be expected if the co-products (linseeds and grass hay) should be grown and harvested in separate systems. However, if economic allocation is used, the contribution to nutrient enrichment from the flax system increases by a factor 2 or more.

The main contribution in the paper wool and flax systems comes from airborne emissions of nitrogen oxides related to combustion of fossil fuels, contributing more than 80% of the total. In the stone wool system, the main contribution comes from emissions of ammonia in the final production process, accounting for about 75% of the total, while nitrogen oxides account for the major part of the remaining 25%. According to the EDIP method, emissions of COD do not contribute to nutrient enrichment, and play only a very minor role in either system when the CML impact assessment method is applied.

3.4 Photochemical ozone formation

The potential for photochemical ozone formation (POCP) differs from the previous impact categories with stone wool having a significantly larger contribution (factor 10–20) than the two other materials.

The main contributor to POCP in the stone wool system is carbon monoxide emitted from the production process. This accounts for about 80% of the total contribution. The emission is assumed to be associated with the use of coke as a fuel, however, this cannot be confirmed because the inventory is based on measurement of the emissions from the combined production process.

In the other two systems, the POCP is associated to a large number of small contributors, mainly industrial combustion processes. Whereas these account for only 20% in the stone wool system, they account for the total in the paper wool and flax systems, where only insignificant amounts of carbon monoxide are emitted.

However, even if the amount of carbon monoxide from stone wool production is reduced by installation of an afterburner similar to that used at the U.K. Rockwool® plant, stone wool will still have a larger contribution (factor 2–3) than the two other systems. This indicates strongly that there is a significant difference with respect to POCP between stone wool and the two other systems, but it should be noticed that the inventories for industrial combustion and production processes often are of a relatively low quality in relation to compounds contributing to POCP.

3.5 Hazardous waste

The handling of waste as a single or two impact categories causes some problems, because of the many waste definitions encountered when using inventory information from a broad range of sources. When combined, the inventories for the three products comprise no less than 18 waste categories, ranging from highly radioactive waste to waste for recycling (overburden waste has been omitted from the waste considerations).

It was chosen to aggregate five waste categories (hazardous, chemical, regulated chemicals, radioactive and highly radioactive) under the heading 'hazardous waste', while the remaining categories are aggregated under the heading 'non-hazardous waste'. This means that the sum results can only give a very crude indication of the performance of each system and that the comparison between the systems should be interpreted with great caution.

Also for hazardous waste, it is questionable whether the calculations give a realistic picture. As mentioned earlier, no international agreement has been achieved on the classification of different waste types in LCA, and the accumulated amounts can therefore hardly be compared on a more objective basis.

Thus, it is an open question whether the significant difference between the paper wool system and the other two systems is an expression of real-life conditions. The main contribution in the paper wool system comes from the newsprint production, with production of borax and boric acid being two other main contributions. Both sources for these inventories (KCL, Finland, and Borax Rio Tinto, USA) are assumed to be of relatively high quality, and it is therefore possible that the amounts give a realistic picture of classified waste fractions in the production. For stone wool, the main contribution comes from briquette production (more precisely to the energy consumption in cement production) and from the final production process. For flax, the contribution comes from numerous small sources. Overall, the results suggest that paper wool generates substantially more hazardous waste than either stone wool or flax. However, it is noted that the data quality – as for non-hazardous waste – is generally low.

3.6 Non-hazardous waste

The flax system produces the largest amount of non-hazardous waste of the three systems, 2.5–4 times more than the other two systems. The main contribution comes from production of the electricity consumed in the production of insulation mats. The database used specifies that 14.1 g/MJ of 'bulky waste' results from electricity production, but it is not possible to get more specific information about the nature of the waste. A large fraction is assumed to be overburden from coal extraction, but this assumption cannot be verified from the information in the database. Another large fraction of the non-hazardous waste from electricity production is slags and ashes (3.25 g/MJ).

Other main contributions to the formation of solid waste in the flax system are mineral waste from production of PET and industrial waste from production of DAP. It has not been possible to establish more precise information for either of these amounts.

For stone wool, the main contribution comes from the final production process and is also associated with consumption of electricity. Other main contributions come from briquette production and from landfilling of PE-packaging waste; the latter constitutes about 20%.

For paper wool insulation, the main contribution comes from production of aluminium hydroxide and from the paper production process. Neither of these contributions is related to energy consumption, or at least only to a limited degree.

It is not possible to draw firm conclusions regarding waste amounts because of the rather poor quality and differences in waste categories of the basic data. The problem can only be solved satisfactorily by avoiding waste as an impact category, e.g. by a closer examination of the fate following disposal. Therefore, the figures given in the report are only crude suggestions of relative importance and should not be over-interpreted.

3.7 Energy consumption

The energy consumption has been assessed by looking at total primary energy consumption as well as for each of the subcategories for which information has been collected. There are, however, significant differences with respect to the types of energy used in the three systems, and these are discussed in more detail in the following sections.

3.8 Consumption of fossil fuels

When comparing the use of fossil fuels it is evident that the flax system is the most demanding, followed by the stone wool system (using 60% of the amount in the flax system) and paper wool (using only about 25% of the amount of the flax system).

The main reason for the comparatively large use in the flax system is the use of polyester binder, accounting for 15% of the weight of the final product. Polyester (PET) is – when compared to the other major raw materials examined in the present study – relatively demanding in terms of energy consumption in production (about 84 MJ/kg) and accounts for almost half of the fossil fuels used in the flax system. A large fraction (about 40%) is feedstock energy, which in principle can be recovered by incineration at the end of the useful life of the insulation. However, incineration is not seen as a common disposal process in the future, because the insulation material will be mixed with other demolition waste that only is suitable for recycling in road construction or other applications with low demands to material quality. The different disposal options are discussed in more detail in the sensitivity analysis of the flax system, but it is mentioned here that, in order to reach a comparable level of fossil energy consumption, at least 50% of the flax insulation must be collected separately from other construction materials and incinerated with recovery of the inherent energy. Another main consumption of fossil fuels takes place in the final production of flax insulation. Again, it can be assumed that the polyester binder is responsible to a large extent, because the binder needs energy to be melted and extruded as fibers.

The stone wool system examined in the current project performs very much in the same way with respect to fossil energy consumption as was reported by Bowdidge [1]. The production process is responsible for more than 90% of the fossil energy consumed, but the consumption in the present study is 10% less than reported by Bowdidge (16.6 MJ/kg vs. 18.4 MJ/kg). This difference can probably be attributed to differences in process efficiency and/or a better energy management at the Danish production site.

In the paper wool system, newsprint production accounts for about 50% of the consumption of fossil fuels, production of additives accounts for 40%, and transportation for about 10%. As for the flax system, disposal by energy recovery is not assumed to be a common disposal method in the future. The possibilities are perhaps even less for paper wool because of the state of the material following demolition. However, it is mentioned here that incineration of 50% of paper wool following the use phase will decrease the consumption of fossil fuels to only about 2 MJ/kg, because the renewable fuel paper wool will displace fossil fuels in production of heat and electricity.

3.9 Consumption of renewable fuels

The paper wool and flax systems consume equal amounts of renewable fuels, about 20 times more than the stone wool system. For paper wool, the main part (more than 95%) of the renewable fuel is feedstock (wood) in the basic raw material, newsprint. As discussed in the previous section, it is theoretically possible to recover a large part of the inherent energy by incineration, but the nature of the paper wool waste makes this option less viable, also in the future. If incinerated, the flame-retardants (borax, boric acid and aluminium hydroxide) will decrease the heat value of the paper. This decrease is included in the calculations that are based on actual measurements of the heating value of final products that can be found on the market today. The consumption of renewable fuels in the flax system is also primarily related to the feedstock content in the product.

3.10 Electricity consumption

The flax system consumes most electricity of the three systems, more than twice the amount of the stone wool system and about 50% more than the paper wool system. For flax and stone wool, the main part of the electricity consumption takes place in the final production stage, while for paper wool the main consumption is found in the production of newsprint.

3.11 Overall energy consumption

The flax insulation system has the largest total primary energy consumption, 250% larger than the stone wool system and twice as large as the paper wool system. Stone wool insulation is the least demanding with respect to overall consumption of primary energy, consuming only 40% of that for flax and 80% of that for paper wool. The largest part of the energy consumed in the stone wool system is based on fossil fuels, but even when taking this aspect into consideration, stone wool performs significantly better than flax insulation. Paper wool is the least demanding with respect to fossil fuels (about 40% of the consumption in the stone wool system), but with respect to the overall consumption, paper wool consumes more energy, primarily because of the large amounts of feedstock in the product that cannot be exploited following use.

4 Comparison of Health Aspects

Adverse effects of concern for fibres are mechanical skin irritation caused by friction of coarse fibres and a possible hazard of developing respiratory diseases including fibrosis and cancer.

4.1 Stone wool

Due to the effect of coarse fibres, Commission Directive 97/69/EEC classifies mineral wool (including stone wool) as a skin irritant with risk phrase R38.

In a review article from 1996 it is concluded that there is no convincing evidence that exposure to mineral wool (stone and glass wool) is a risk factor for impaired lung function or fibrosis in the lung [2].

In recent years, HT stone wool (high-alumina, low-silica wools) has been increasingly replacing traditional wool [3]. The reasoning behind being that the potential danger of a specific fibre is mainly dependent upon the extent to which the fibres can be inhaled and can persist in the lung [4]. The lower the biopersistence (or the higher the biosolubility) the less potential pathogenic is a specific fibre type. The development and implementation of the less biopersistent HT stone wool, instead of traditional stone wool, has increased the safety margins in manufacturing and use of fibrous insulation materials [3,5,6].

Mineral wool (stone wool, glass wool) is within the EU by Commission Directive 97/69/EEC classified as carcinogenic in Category 3 (possibly carcinogenic). However, 'Note Q'[1] in the EU Commission Directive 2001/59/EC of 6 August 2001 allows for derogation (exemption) from classification as a carcinogen. The animal test results according to 'Note Q' for the HT stone wool fibres were below regulatory thresholds and were therefore not classified as carcinogens within the EU [6].

Also, the HT fibres have previously been tested in a long-term inhalation study in rats and produced no lung fibrosis and no significant increase in the incidence of lung tumours and no mesothelioma [5]. In addition, in a study in rats HT fibres administered by intraperitoneal injection (i.p.) at a high dose showed no abdominal tumours [7].

A recently published investigation evaluated to what extent various insulation materials (including stone wool, flax and paper wool) influenced the working environment. To ensure a high degree of comparability between the different materials, the tests were done at full-scale simulation in an experimental hall. It was concluded that the installation of HT stone wool could be performed without use of respiratory protection [8].

4.2 Paper wool

In comparison, paper dust has been shown to cause cancer by injection in test animals as well as lung fibrosis by inhalation [9,10]. Furthermore, paper fibre is biopersistent [11] and the dust formation during handling often exceeds the Threshold Limit Values, requiring the use of respiratory protection in the work situation [8]. The potential for paper dust to cause cancer by inhalation has not been investigated, and this is a knowledge gap, which should be rectified.

4.3 Flax wool

The toxicological properties of flax fibres are, to a large extent, unknown. Exposure to flax dust is a well-known cause of the lung disease byssinosis (Greek: *byssinosis* = flax) [12], but the carcinogenic properties and the potential for causing lung fibrosis have not been investigated in any detail. By analogy to paper fibre, flax is assumed to be biopersistent and the potential for dust formation warrants the use of respiratory protection [8].

4.4 Additives

Organic based insulation materials are flammable and need addition of flame-retardants and sometimes biocides. The most common flame-retardants are boron compounds or aluminium compounds. Ingestions of boric acid or borax in drinking water or food have caused testicular damage in experimental animals, and boron compounds have been classified by the EU Working Group on Classification and Labelling of Dangerous Substances as reproductive harmful with R-phrase 62 (possible risk of impaired fertility) and R-phrase 63 (possible risk of harm to the unborn child). The aluminium compounds used as flame retardant in these insulation products are not considered hazardous by the EU. The results of the human health assessment are summarised in **Table 3**.

5 Ranking of the Three Product Systems

In **Table 4**, the three product systems have been ranked according to their performance in each impact category. This subjective assessment is based on actual differences between the systems in combination with the overall data quality of the LCA's performed and the precision of the impact assessment methods for each impact category.

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[1] Note Q: The classification as a carcinogen need not apply if it can be shown that the substance fulfils one of the following conditions:
- a short term biopersistence test by inhalation has shown that fibres longer than 20 µm have a weighted half-life less than 10 days, or
- a short term biopersistence test by intratracheal instillation has shown that fibres longer than 20 µm have a weighted half-life less than 40 days, or
- an appropriate intra-peritoneal test has shown no evidence of excess carcinogenicity, or
- absence of relevant pathogenicity or neoplastic changes in a suitable long term inhalation test.

Table 3. Comparison of animal and human evidence for chronic effects and possible exposure levels relative to Occupational Exposure Limits (OELs)

	Animal evidence				Human evidence		Exposure
Fiber dust	Carcinogenicity		Lung fibrosis by inhalation	Biopersistence	Non-malignant lung disease	Cancer (IARC)	OEL[2] Exceeded (Breum et al. 2002)
	Inhalation	Injection					
Traditional stone wool	No	Yes	Yes	No	No	No	No
HT stone wool	No	No	No	No	No[3]	No[3]	No
Cellulose shredded paper	Not tested	Yes	Yes	Yes	Not tested	Not tested	Yes
Cellulose flax	Not tested	Not tested	Not tested	(Yes)[1]	Yes	Not tested	(Yes)

[1] No experiments have been performed but the fibers are most likely biopersistent (durable) in lung due to chemical/physical similarity to other cellulosic fibers.

[2] OEL for unspecified organic dust = 3 mg/m^3 total dust; OEL for organic fibers do not exist but the OEL as for stone wool = 1 respirable fibers./cm^3 has been used.

[3] Due to similarities to traditional stone wool in chemical components.

Table 4: Ranking of the three product systems with respect to different impacts (1 = best, 3 = worst, ? indicates that there is no available information, and * indicate that the differences are evaluated to be significant within the given system boundaries)

Impact category	Unit	Stone wool	Flax	Paper wool
Global warming	g CO_2-equivalents	2*	3*	1*
Acidification	g SO_2-equivalents	2	3	1*
Nutrient enrichment CML-method	g PO_4^{3-}-equivalents	2	3	1*
Nutrient enrichment EDIP-method	g NO_3^--equivalents	2	3	1*
Photochemical ozone creation	g C_2H_4-equivalents	3	2	1
Generation of solid waste	g non-hazardous waste	2	3*	1
Generation of hazardous waste	g hazardous waste	2	1	3*
Fossil fuels (incl. feedstock)	MJ	2*	3*	1*
Renewable fuels (incl. feedstock)	MJ	1*	2	3
Electricity	MJ	1	3*	2
Total energy consumption	MJ	1	3*	2
Water consumption	g water	2	3	1
Health aspects in general		1	3	2
Carcinogenicity in animals		1*	Not tested	3
Lung fibrosis in animals		1*	Not tested	3
Fiber biopersistence in animals		1*	3	3
Non-malignant lung disease in humans		1	3	?
Skin irritation in humans		3	?	?
Reaction to fire		1*	3	3

It is a general picture that flax insulation is most demanding in the examined impact categories, with formation of photochemical ozone and generation of hazardous waste being the exceptions. This may be somewhat surprising as flax in itself is a renewable material, but is explained by the use of a relatively large consumption of non-renewable materials as important components in the product. This consumption adds significantly to both energy consumption (incl. fossil fuels) and the examined impact categories that, to a large extent, are related to emissions from energy consumption.

Another general picture is that the paper wool system performs best in most impact categories, with total energy consumption and generation of hazardous waste being the exceptions. This cannot be regarded as a surprise, as paper wool, to a large extent, is based on renewable resources and only consumes a relatively small amount of non-renewable resources which themselves are relatively undemanding in terms of consumption of fossil fuels.

The performance of the stone wool system lies in between flax and paper wool in most of the examined impact categories, with total energy consumption being an important exception. The stone wool system consumes a relatively large amount of fossil fuels in the production phase, but none of the raw materials entering the system are demanding in terms of non-renewable resources. As evidenced by the contribution to photochemical ozone formation, it is still possible to improve the environmental performance in specific areas (and at specific production sites), but stone wool must generally be regarded as a fully developed product system providing a sustainable option.

With respect to health aspects, it is concluded that modern HT stone wool is neither carcinogenic nor does it cause serious lung diseases. It is more biosoluble than traditional stone wool and there is no (or minimal) risk of exceeding the occupational exposure limits. In comparison, paper dust has been shown to cause cancer by injection in test animals as well as lung fibrosis by inhalation. The potential for causing cancer by inhalation in animals has not been investigated. The toxicological properties of flax fibers are, to a large extent, unknown. Exposure to flax dust is a well-known cause of byssinosis but the carcinogenic properties and the potential for causing lung fibrosis have not been investigated in any detail. The missing investigations on paper dust and flax fibers are of great concern, also because there is a great risk of exceeding occupational exposure limits during handling. Use of respiratory protection is therefore a must when handling the two materials. Based on available information the potential health hazard ranking for these three materials are: stone wool < paper wool < flax.

As a final remark, it is emphasized that each of the systems, irrespective of their environmental performance during production and disposal, has a positive influence on the environment because of their ability to reduce energy consumption in buildings. The energy savings during use amounts to more than 100 times of the invested energy, and the benefits from adding more insulation will clearly outweigh any drawbacks from the production and distribution, also when national requirements have already been fulfilled.

There are still major opportunities for improvement with respect to the final disposal of especially flax and paper wool, at least in relation to the basic recycling assumption that has been applied in the present study. For flax and paper wool incineration by energy recovery seems to the best alternative, unless producers can find a way of re-using the products after their first life in a building. Re-use should however only be applied if absolute certainty of insulating properties can be obtained, because otherwise a large and unnecessary heat loss may be the consequence. For stone wool, it is possible to re-use waste products, and this will cause a smaller consumption of (abundant) stone materials.

6 Final Conclusions and Outlook

It is acknowledged that the study is scoped to cover only a part of the insulation products on the market today, because it is a comparison between products based on two organic materials with one traditional mineral material. A comparison with glass wool, polystyrene and polyurethane products would also be interesting. The study pinpoints some main characteristics of three important materials, not only in relation to their impacts on the natural environment, but also to occupational health, which for many construction companies and workers are seen as an equally important issue.

With respect to potential environmental impacts, stone wool and paper wool are the most preferred materials. Stone wool has the smallest consumption of primary energy 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, caused, to a large extent, by the binder used, which is an essential component.

The differences in environmental impacts from the production and disposal of the three materials are, in this context, only of minor importance. The quality of the products (their fitness for use throughout their entire life time) may in the end prove to be the determining factor, because a reduction in the insulation capacity will cause much larger impacts than those observed during the production and disposal of the products.

With respect to occupational health and safety, stone wool emerges as a material with a thorough documentation for its toxicological properties. The toxicological properties of flax and paper wool are not documented to the same extent. Absence of serious potential impacts on human health is seen as an integral part of product quality, and for that adequate documentation is missing for paper wool and flax. Based on available data, HT stone wool seems to be the most tested, well-known and safest choice of the three as regards potential health hazards.

Finally, it must be recognised that in the long run insulation of buildings by saving energy probably saves more than 100 times the environmental impacts associated with the production and disposal of the products used for insulation. Thus, all three insulation products examined with respect to their potential impacts on the environment and human health provide a large benefit to the environment in the life cycle perspective. The quality and fitness for use of an insulation product throughout its useful life may be the most important aspect. Seen in view of this and the inherent uncertainties in the LCA, the differences between suitable products are of minor significance as demonstrated in the present study.

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