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Carbon footprint and energy use of textile recycling techniques

Case study: Sweden

Master of Science Thesis

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Abstract

In Sweden approximately 15 kg of textile is consumed per person annually, from which 53% of the consumed textile and garments are incinerated with the aim of energy recovery. 20% is collected by charity organizations with the aim of reusing and the rest is either stored in closets or treated by other waste management methods [2].

Since there is no existing textile recycling plant in Sweden, from sustainability perspective it would be beneficial to explore different textile recycling techniques and to investigate their feasibility. An ongoing research program aims at developing sustainable waste management strategies. It is called Towards Sustainable Waste Management and is directed by IVL Swedish Environmental Research Institute.

This study is conducted with the aim of quantifying the energy usage and global warming potential of different textile recycling techniques in order to evaluate the environmental benefits of the different options. An LCA with restricted scope is applied for quantifying the carbon footprint and energy use of suggested textile recycling techniques and comparing the results with incineration as the base case. Evaluating sustainable textile recycling techniques can contribute to the goals of the research program at IVL.

Preface

This project was performed at IVL Swedish Environmental Research Institute as a 60 credits Master thesis to finalize my master studies in Innovative and Sustainable Chemical Engineering at Chalmers University of Technology.

The completion of this project would not have been possible without the guidance and support of several people. First of all, I would like to express my deepest gratitude to Tomas Rydberg for his invaluable support and guidance during this study. My sincere thanks to David Palm for being my supervisor and providing great amount of help and Magdalena Svanström for her contribution to our meetings as my examiner.

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Finally and most importantly, my deepest appreciation to my Parents (Susan and Reza) for their unending support, love and concern about me.

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1. Introduction

Many persuasive reasons would lead to recycling of textile waste, such as new alternative of low cost raw materials for the products. The rate of recycling of textiles, however, is low because of inadequate public willingness to adapt to other types of waste disposal and taking part in recycling [1].

Global population growth and improvements in living standards have caused an increase in consumption of textiles, and in turn to growing textile production during the past few decades [1]. As an example, in Sweden, approximately 141 million tonnes of textiles are consumed annually [2]. The major usage areas of textile could be categorized as: apparel, home furnishing and industrial applications [1].

The concept of over consumption in textile industry is derived from the idea behind fashion industry. The definition of fashion increases the demand for changes and generates more requests for replacement of the products with fresher and more modern goods. The recent idea of "seasonal new collection" in apparel industry encourage consumers more in purchasing more clothes .Increase in bying of fashinable apparels raises rate of textile consumption. Consequently more textile waste will be created [3].

Major components of textile products are natural and synthetic polymeric materials including cotton, polyester, nylon, and polypropylene [1]. The source of raw materials for synthetic polymers is petroleum, which is a non-renewable resource. Even the production of renewable natural polymers demands non-renewable resources as a supply of energy [1].

Many types of methods exist for textile waste management. One of them, reusing products in their original form, is common practice to recover waste streams. Another option is recycling of textile waste to various usable products with the aim of recovering textiles. The predominant method of textile waste treatment in Sweden is incineration [3].

Although recycling of textile waste implies environmental benefits, it confronts many challenges such as :

- Demand for a certain amount of energy during the mechanical, chemical or biological processes which are involved in recycling of waste into products
- Need for additional raw materials throughout the recycling processes
- Emissions into air, water and soil would occur during the recycling processes [1].

Thus, for evaluating the benefits of the recycling schemes, the following factors should be considered:

- Whether the energy consumption and pollutant emissions of the recycling process is compensated for by the manufacturing of the products from virgin materials that would otherwise have to be performed
- Whether the recycled products have potential markets and competitive costs [3].

1.1 Textile waste management

Textile waste consists of post-consumer textile waste, including any type of discarded garments and household articles made out of textiles, and pre-consumer textile waste containing by-products or residues from processes in home furnishing, apparel, furniture, automotive or other industries [4].

Textile waste treatment strategies include reducing, reusing, recycling and energy recovery. Large amounts of textile waste are today managed by applying methods of reusing and recycling [3]. Reusing of textiles means using the article again with the same functionaliy. Recycling of textile waste involves breaking down the textile products and using components for producing new items [1] [3].

1.1.1 Reuse of textiles

Reuse of textile waste can be done in different ways. Common practice includes second hand shops releasing clothes into the marketplace for another round, the collecting done by charity organizations or informally among family members. If excluding second hand goods used locally, large amounts are shipped abroad for selling on global market or to other local traders in Eastern Europe or Africa [3]. According to statistics, 26 000 tonnes of used apparels and shoes were collected by charity organizations during 2008 in Sweden, with the aim of donating them to Africa and Eastern Europe [2].

Reuse of textile products has environmental benefits. In order to assess the amount of energy saved and avoided emissions by applying reuse of apparels and discarded textiles, the amount of energy usage and greenhouse gas emissions during collection, sorting and reselling of the used clothes should be calculated and compared with the energy demand and emissions of manufacturing new products [2].

1.1.2 Recycling of textiles

Another option for potentially saving resources in waste management is recycling. Lack of technological innovation and existence of cheap fabrics in markets today limits the interest and possibility for applying recycling techniques; however new technologies for recycling textile waste are developing [3].

Moreover, various types of fibers and mixed colors of fabrics are considered as limiting factors in textile recycling, since they affect the sorting processes negatively and decrease the quality of recycled materials.

A summary of different textile recycling processes is presented below:

Mechanical recycling of textile waste:

Different mechanical techniques exist for recycling of textile waste. The applicability of each method depends on the quality of discarded textiles.

Techniques to produce fabrics: Discarded high quality fabrics are used in a remanufacturing process in order to turn it into different types of products. There are some remanufacturing units in UK, such as Worn Again or Motties. Textile waste is then converted into a new product by deconstructing it and finding uses in re-production as textile wallets or slippers [4].

Techniques to produce yarns: Some mechanical techniques are applicable for producing yarns out of used textile. Their properties are dependent on the quality of the textile waste utilised. Yarns produced from recycled textiles with poor physical properties consist mostly of mixed color fibers and various fiber lengths and their usage is limited to manufacturing of synthetic technical textiles, such as geotextiles or woven filtration systems [4].

Techniques to produce fibers: The concept of this process is to open up the structure of the discarded fabric by means of cutting. Afterwards, the broken down textile is passed through a drum rotating surface several times to obain fibers. The gained fine felt can be dyed or blended with virgin fibers and spun to yarns if required [3]. Furthermore, after-treatment methods are needed for enhancing the quality of the fibers, elimination of short fibers, cleaning from dust and, if needed, blending with primary fibers [4]. Various types of textile waste can be used; the quality of the gained fibers, however, is dependent on the type of textile waste. A large part of fibers gained from textile waste will be used for manufacturing nonwoven products such as upholstery, carpet underlay, sound and heat insulation materials in automotive industry, disposable diapers, napkins and tampons. Yarns made from this type of fibers are dark or gray in most cases, hence not typically found in household textiles [4]. Textiles produced from these fibers can be applied either in higher grade products such as sheeting, furnishing and apparel or lower grade products such as wiping and fillings. The characteristics of the particular fibers would determine potential applications [4].

Chemical recycling of textile waste:

Besides the mechanical recycling methods, synthetic fibers can be chemically recycled. Chemical processes are applicable for fibers such as polyester, nylon or polypropylene. According to theses processes, fiber molecules are broken down and the feedstock is repolymerized furthermore. Recent technological development are investigated on the repolymerization of recycled synthetic fibers [1][3].

Chemical techniques can also be used for mixed fibers containing synthetic/natural materials .By applying chemical reactions synthetic fibers can be extracted from the mixed materials. Recycled synthetic fibers can be used in home furniture and automotive upholstary [3].

A Japanese company, Teijin fiber Ltd., has developed a closed loop process for recycling discarded polyester apparels with cooperation of Patagonia Inc., in 2000. Uniforms were the main targets for collection during this project due to a high content of polyester and easy collection [4].

According to this process, the end of life polyester apparel would be turned back into a raw material with enough quality to be used as the original polyester for manufacturing new products.

First, the polyester products would be broken down into small pieces, granulated to pellets and decomposed to the raw material, DMT (dimethyl terephthalate), by using chemicals. DMT can be polymerized again and spun into new polyester fibers [8]. One of the disadvantages of this process is the need for complete separation of polyester fabrics from other types of fabrics such as polyester/cotton, acrylic, wool, polyurethane or leather [8].

Separation by using NMMO

There are ideas circulating around the Lyocell process, for making it applicable in textile waste recycling industry. In the Lyocell process, N-methylmorpholine-N-oxide (NMMO) is used as a solvent in direct dissolution of powdered cellulose. This process has been applied commercially in companies such as Tencel and Lenzing. The environmental advantage of applying this process comes from using a non-toxic solvent, which is later recycled [5].

In the Lyocell process, wood pulp is dissolved with NMMO. The solution is filtered and cellulose fibers are extracted. Cellulose fibers are then washed and dried. Wash liquors are circulated in a recovery system to reuse the NMMO [6].

Recycling textile waste by using NMMO as the solvent in combination with separation of cellulosic fibers from polyester could be developed further, since polyester is the most popular synthetic polymer in textiles. In the first step, blended textiles would then be cut into pieces and mixed with NMMO (85% w/w NMMO concentration) [5][7]. Dissolved cellulose would afterwards be separated from the polyester residue by filtration. The remaining polyester would be washed and sent for further recycling.

1.2 Opportunities in textile recycling

Despite the fact that reusing is a more preferable waste management option in the waste hierarchy than is recycling or energy recovery, it is not always viable for all types of textiles. Nowadays, in Europe, most textile waste that is recycled is recycled mechanically into fibers for use as fillings in mattresses and for upholstery. A smaller portion of these recycled fibers is available to manufacture various types of products such as thermal insulation or capillary matting [4].

Due to the poor quality of recycled fibers and fabrics, there is still a large tendency to use virgin natural and man-made fibers, which could cause a decline in recycling of textiles [3].

Recycling of textiles to lower quality products is not very challenging, as the products require less stringent compositional and mechanical properties. Nevertheless, to recycle textiles into higher quality products, some factors have to be considered in the first life stage of textiles, such as reduction or prevention of fibers mixtures and increasing usage of single fiber types in textiles.

One of the obstacles in developing technologies for recycling textiles is the low value and diverse qualities of the inlet flow [4].

1.3 Life cycle assessment

Life cycle assessment (LCA) can be applied to define the environmental performance of a product from cradle to grave. All the processes including extraction of new materials, production phase, use phase, waste treatment and its disposal, would be assessed in LCA.

Two different methodological approaches can be applied in LCA: attributional LCA and consequential LCA. Attributional LCA can be used with the aim of estimating a product's environmental impact and to compare it with other products. Consequential LCA can describe the effects of changes applied within a system[9].

According to ISO 14044, life cycle assessment includes four steps, see Figure 1:

- Goal and scope definition
- Inventory analysis
- Impact assessment
- Interpretation

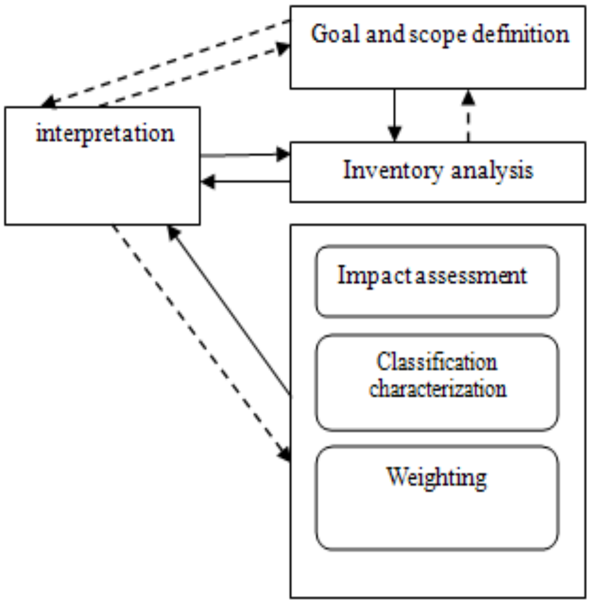


Figure 1. LCA procedure based on Baumann and Tillman [9]

During the definition of the goal and scope, the purpose of the project and questions that should be answered are defined. The functional unit is defined and expressed in quantitative terms. The functional unit is used as a basis of calculations and in impact assessment. Another task during goal and scope definition is clarifying boundaries, activities and included parts of the system. In addition, geographical and time boundaries, and emissions that will be included in the assessment, should be decided on [9].

The effects on the environment that are assessed include impacts from various emissions, resource use and land usage. Environmental impacts can, according to the ISO standard, be categorized into human health, resource use and ecological consequences. These primary groups can be further described as potential impact categories such as global warming potential, acidification potential, eutrophication potential and resource depletion. The final step of the goal and scope definition is selecting the environmental impacts to be assessed [9].

The first step in the inventory analysis is the creation of the process flow chart based on the assumptions considered in the goal and scope definition. The functional unit would be shown as the reference flow in the flow chart. Next, appropriate data about the processes will be collected. In this step, inventory of input material, energy flows, emissions and output waste within the system boundaries of the processes are defined [9].

The data obtained during the inventory analysis will be processed in the impact assessment, containing up to three different steps: classification, characterization and weighting.

According to the classification step, inventory parameters are classified into environmental impact categories sich as global warming potential, acidification, primary energy usage and other groups, based on their potential impact. During the characterization step, science-based conversion factors are used to calculate the results within the impact categories. Characterization of the results means multiplying the results with set equivalency factors and summarizing them into different impact groups.

Weighting is an optional step for highlighting the most important potential impacts. Here, different weighting methods, such as Eco-indicator 99 or EDIP, can be applied for summarizing the results in the impact assessment, resulting in a single number that is more convenient to communicate. On the down-side, when summarizing all the results into a single number, some critical details could be neglected.

In uncertain situations, some tests, such as data quality analysis by sensitivity analysis or uncertainty analysis, can be applied. For example, when data might not be available or has poor quality, uncertainty analysis can be used to determine the results of different ranges of data. The robustness of data and assumptions made, however, are investigated in sensitivity analysis [9].

1.4 GaBi software

GaBi sustainability software has been used for building case models and simulating the systems from a life cycle perspective. Models for any process can be created in GaBi in order to calculate emissions, primary energy usage and material input and outputs [10].

2. Methodology

2.1 Goal and scope

The aim of this project is to determine if recycling techniques of discarded garments and household textile waste would actually result in a net environmental benefit. The proposed recycling techniques would replace incineration, which is the dominant method of textile waste treatment in Sweden. In this study, LCA is applied to determine the environmental impacts attributed to textile recycling techniques for household textile waste. Net avoided energy usage and greenhouse gas emissions of the recycling techniques are evaluated and compared to those of incineration.

Different recycling techniques for household textile waste will be investigated in this study. The focus lies on global warming and energy usage of the recycling techniques. The net global warming potential and primary energy usage of each system will be investigated and compared with the base case (incineration). Eventually, global warming potential and primary energy usage will be calculated for the scaled-up case of a combination of the textile recycling techniques. The intake of this system amounts to the textile waste produced annually in Sweden. In this study, carbon dioxide emissions, bundled with methane and nitrous oxide, are considered as contributing to global warming potential.

2.2 Scenarios

There are four waste treatment options that are compared in this project. As incineration is the current process for textile waste treatment in Sweden, it is considered to be the reference case. Other recycling techniques have not yet been applied in large industrial scale, but have shown potential to be significantly practical.

Below is a short description of the scenarios:

- Remanufacturing process: the remanufacturing process is based on reusing worn out clothes and old textile to produce new textile products. So far this process has been applied within small industries.
- Closed loop recycling of polyester: here polyester of a certain grade will be turned into dimethyl terephthalate (DMT) and polymerized to polyester granules in a closed loop. Since the technique has been applied by Patagonia Co., it will be named Patagonia process from here on.
- The NMMO process: a conceptual process derived from the Lyocell process, in which cellulosic fibers are obtained from dissolving pulp by using NMMO (N-methylmorpholine-N-oxide) as solvent. Adding NMMO as a solvent of cellulose will separate polyester and cellulosic fibers of textile waste. The process has not been applied in industrial scale, and further technical development is needed for assessing the feasibility of the process. Henceforth the process will be named Lyocell process.

2.3 Functional unit

The first part of the study includes investigating the environmental profile of each recycling technique and comparing them to incineration. In this phase, the functional unit is considered as *waste treatment of one tonne of household textile* by each technique. The type of textile waste considered is discarded household textiles, consisting of 50% polyester and 50% cellulose.

The second part of the study includes the comparison of the environmental impacts of the combined scenarios with the existing treatment system in Sweden. Therefore the functional unit is chosen as *treatment of the total intake of household textile waste in Sweden,* which equals to 1.41×10^{8} kg annually [27][28].

2.4 System boundaries and delimitations

The geographical boundaries for use of the recycling techniques are limited to Sweden. For system expansions, however, no geographical boundaries are considered.

2.5 System expansion

In order to account for other functions of the system than are represented by the functional unit (waste treatment),and thereby allow for comparisons of different scenarios , system boundaries can be expanded. In the expanded system, alternative methods of producing an equivalent amount of product, heat and electricity from virgin resources are included in the assessment. According to the recycling techniques, the product made out of recycled materials will replace a product of the same kind from virgin raw material. In that case, the environmental impacts caused by the equivalent amount of product from virgin raw material, are subtracted from the recycling system in order to account for avoided emissions, and likewise for energy usage. Therefore, environmental interventions may become negative. The amount of energy recovered by incinerating the residues of the processes can replace other alternatives of heat and electricity production.In this study, by applying system expansion, the scenarios would be comparable with each other.

2.6 Environmental impact categories

The inventory data provides different raw materials and the amount of energy required for each step of the process. The environmental impact categories investigated in this study are global warming potential related to the emissions of carbon dioxide, nitrous oxide, methane and the primary energy usage of the systems.

The environmental indicators fall into two categories:

- Resources including renewable and non-renewable energy usage in the scenarios
- Global warming potential$_{100}$ related to the emissions of carbon dioxide, methane and nitrous oxide covered by the CML method in December 2007.

Global warming potential (GWP) is an indicator for the potential greenhouse effect of a specified gas. GWP of a given greenhouse gas is estimated by a relative scale comparing with the same mass of carbon dioxide, for which GWP is standardized to 1 [11].

3. Environmental impact of textile recycling techniques

3.1 Incineration; reference case

3.1.1 Process description

Incineration is the current textile waste treatment technology for energy recovery in Sweden. Here production of heat and electricity, that could replace other energy sources, affects the total environmental impact of the system.

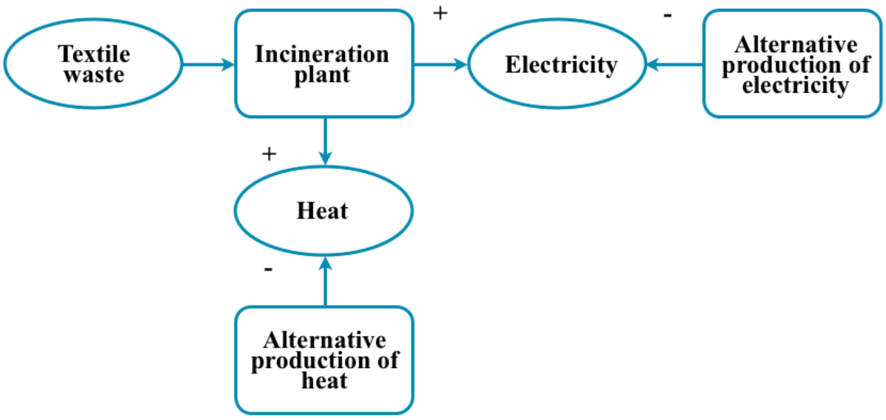


Figure 1. Process scheme of incineration

3.1.2 System expansion

The amount of energy recovered by incinerating the textile waste, can replace other alternatives of heat and electricity production. The alternative process for production of electricity is assumed to be average Swedish electricity mix [23]. Thermal energy from natural gas [23] is considered for heating supply.

The data set for modelling of the system is based on the SWEA model by Palm and Ljunggren *et al.* (2010) [12] based on Björklund *et al.* (2009) [13].

3.1.3 Results

In the figures below, the total performance of the incineration system in terms of global warming potential and primary energy usage are illustrated.

As can be seen in figure 2, results for global warming potential per tonne of treated textile waste for each step of the whole system are presented. The most significant contributor to the global warming potential is the incineration step. The total value of the global warming potential equals to 230 kg CO_2 per tonne of textile waste.

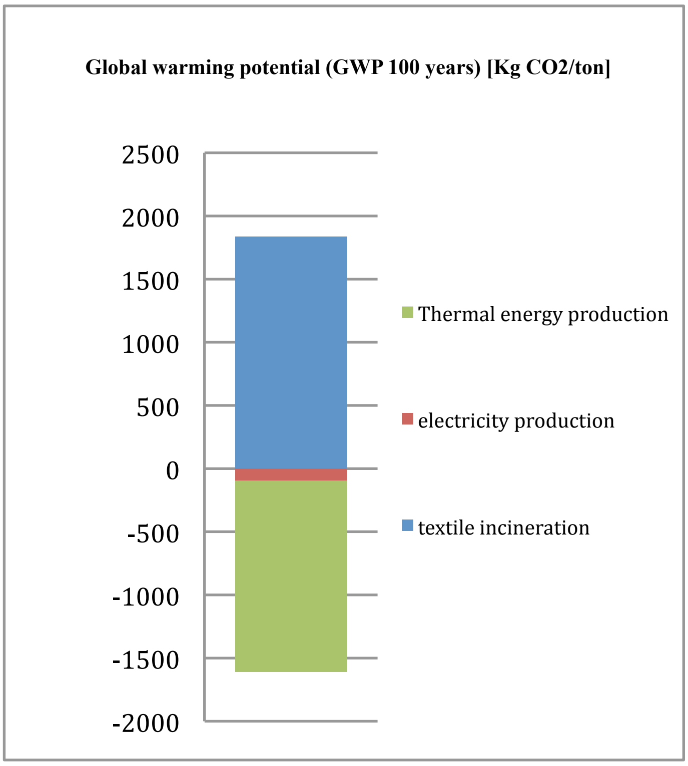


Figure 2. Global warming potential in kg CO_2-equivalent per tonne of textile waste for the incineration system

Figure 3 presents the results for primary energy demand in each step of the incineration system. As can be seen, a large amount of energy is recovered by incinerating the collected textile waste. The amount of energy required for the incineration system is insignificant comparing to the amount of energy recovered by the system.

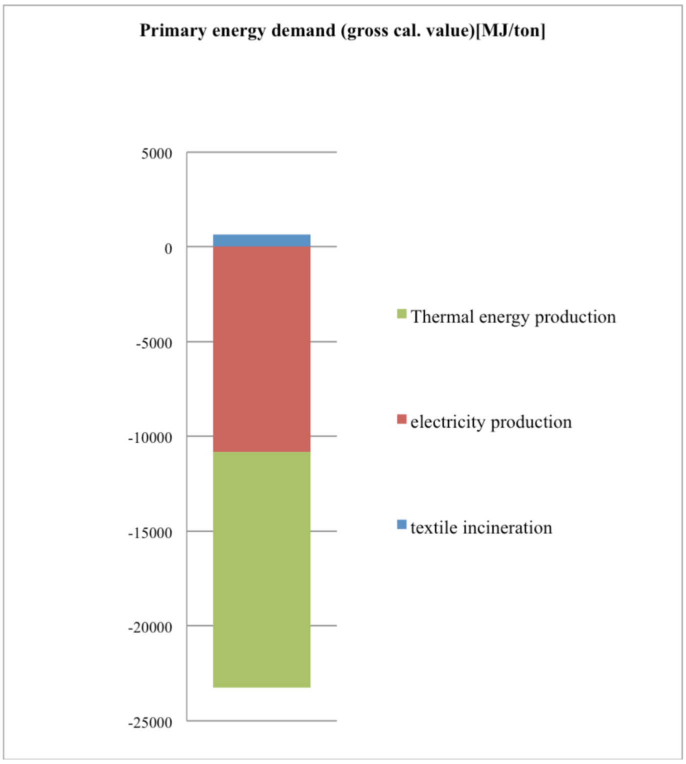


Figure 3. Primary energy demand in gross calorific value for the incineration system

3.2 Remanufacturing

3.2.1 Process description

Remanufacturing is the practice of taking reusable textile waste and transforming it into a product with equal or higher quality. Over the last years some companies, such as Worn Again and Motties, have started to find ways for cutting down textile waste and using it in remanufacturing processes.

According to this process, the whole collected textile waste flow is washed and dried first. Afterwards the reusable discarded textile with high enough quality is separated manually and sent to the sewing machine, about the size for typical home use. The product is assumed to be a textile wallet. The residue of the sewing machine plus the amount of unused textile waste is sent to incineration. It is worth to mention that the whole process is in small scale, however it has potential to be applied in larger industrial scale. Electricity used in this process is assumed to be Swedish electricity mix (from GaBi database) [23]. The thermal energy is assumingly supplied by natural gas (from GaBi database) [23], see figure 4.

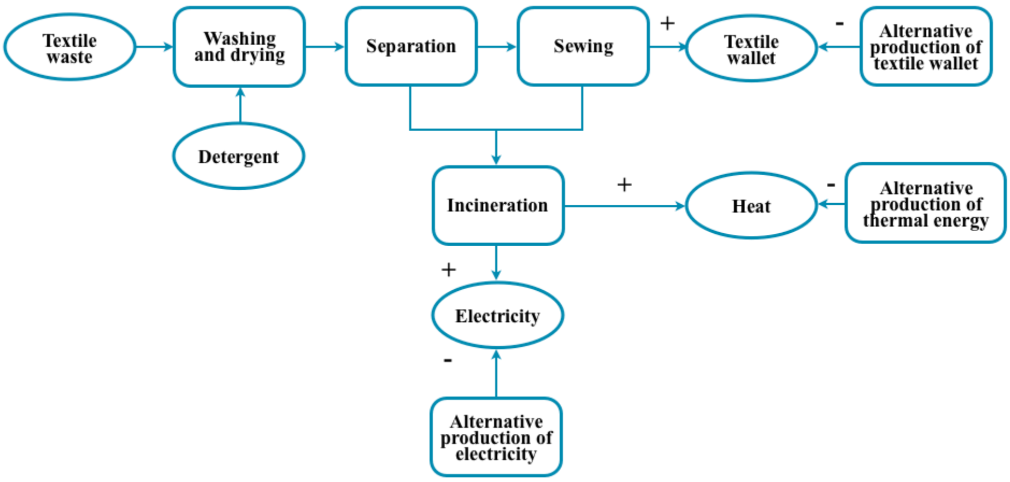


Figure 4. Process scheme of remanufacturing

The data set used for modelling of the process is provided in the table below:

Table 1. Energy consumption in the remanufacturing process

Process	**Energy consumption**	**References**
Production of detergent	Missing	[14]
Separation	Manually: assumed to be zero	-
Washing and drying	Electrical energy: 2562 MJ/ tonne of textile waste	Appendix
Sewing	Electrical energy: 100 MJ /tonne of textile waste	Appendix
Textile incineration	Electrical energy: 19.316 MJ/tonne of textile waste	[11], [12]

The yield of the remanufacturing process is directly dependent on the quality of the collected textile waste and the new product that is manufactured. One of the uncertainties relating to the remanufacturing process is whether the quality of the collected textile waste is high enough to be applied in remanufacturing. The yield of the process is assumed to be 45%.

3.2.2 System expansion

According to the remanufacturing scenario, the textile wallet made out of recycled materials will replace a product of the same kind from virgin raw material. In that case, the environmental impacts caused by the equivalent amount of product from virgin raw material, are subtracted from the recycling system in order to account for avoided emissions, and likewise for energy usage.

Production of textile wallet from virgin materials:

Figure 5 shows the general process scheme of manufacturing textile products from virgin materials:

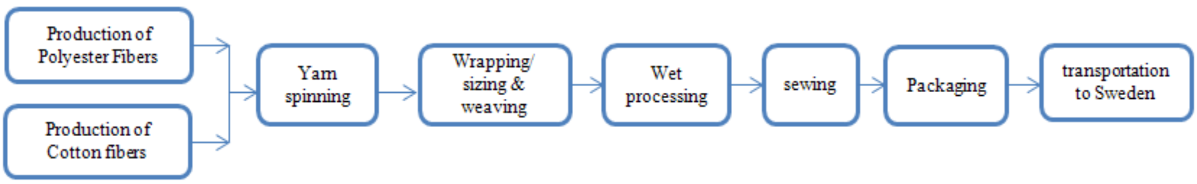


Figure 5. Process scheme of production of textile product from virgin materials

The textile manufacturing process includes fiber production, spinning, sizing, weaving, wet processing and product manufacturing [15]. A considerable amount of energy in the form of thermal and electrical energy are required in textile industry [16]. As can be seen in the flow chart, produced fibers are directed to a spinning process that requires electrical energy to form yarns by twisting and extending the fibers [16]. In order to avoid breakage in weaving, yarns are treated with sizing agents (carboxymethyl cellulose) beforehand. Electrical energy and thermal energy are required for both sizing and weaving processes. The next step is wet processing that includes pretreatment, bleaching and dying. Considerable amounts of thermal energy are needed for this step. Electrical energy is also required for the mechanical parts of the processing machines [17]. It is assumed that the whole process takes place in China and the product is shipped to Sweden. During the process, electrical energy is supplied by Chinese average mix electrical supply and thermal energy is supplied by natural gas, assumingly. Table 2 below shows data used in the inventory analysis.

Table 2. Energy consumption in production of a textile wallet from virgin raw material

Process	**Energy consumption**	**Reference**
Yarn spinning	Electrical energy: 12078 MJ/tonne of fibers	[15]
Wrapping, sizing and weaving	Electrical energy: 7600 MJ/tonne of yarns Thermal energy: 8.5 MJ/tonne of yarns	[16]
Wet processing	Electrical energy: 1920 MJ/tonne of textile Thermal energy: 26780 MJ/tonne of textile	[15]
Sewing	Electrical energy: 470 MJ/tonne of textile	[17]

Data for modeling the process of producing polyester and cotton fibers are according to Kalliala *et al*. (1999)[15] and Palamutcu *et al*. (2009) [17], respectively.

The alternative process for production of electricity is assumed to be average Swedish electricity mix [23]. Thermal energy from natural gas [23] is considered for heating supply.

3.2.3 Results

The results indicate the benefits of the remanufacturing process in which virgin materials are replaced. In the figures below, the total performance of the remanufacturing system in terms of global warming potential and primary energy usage are illustrated.

In Figure 6, results for the global warming potential per tonne of treated textile waste for each step of the process are presented. The negative value of global warming potential relating to the processes of virgin textile wallet production, and electricity production and thermal energy production, indicates the avoided amount of emissions due to the replacement of other processes. As shown in Figure 6, the most significant contributor to global warming potential is production of a textile wallet from virgin raw material. By applying the remanufacturing process, approximately 7000 kg CO2-equiv/tonne of textile waste will be saved according to the results.

The second significant contributor to global warming potential is incineration, as the yield of the system is relatively low and massive amounts of textile residue from the remanufacturing process is sent to incineration. On the other hand, recovered electricity and thermal energy from the incineration plant can cover the energy needs.

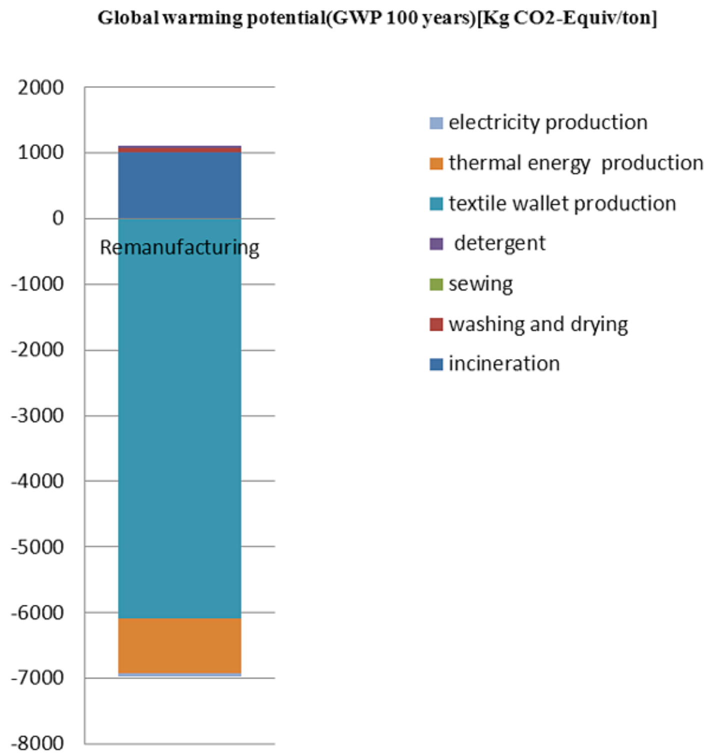


Figure 6. Global warming potential in kg CO_2-equivalent per tonne of textile waste for the remanufacturing system

The results relating to primary energy demand also give a fairly similar picture for the total system performance of the remanufacturing process. Figure 7 illustrates that replacing production of textile wallets from virgin raw material with the remanufacturing process can save significant amounts of energy. The total primary energy usage is in fact negative, since energy-intensive processes, such as production of textile wallets from virgin material, are replaced by the remanufacturing process.

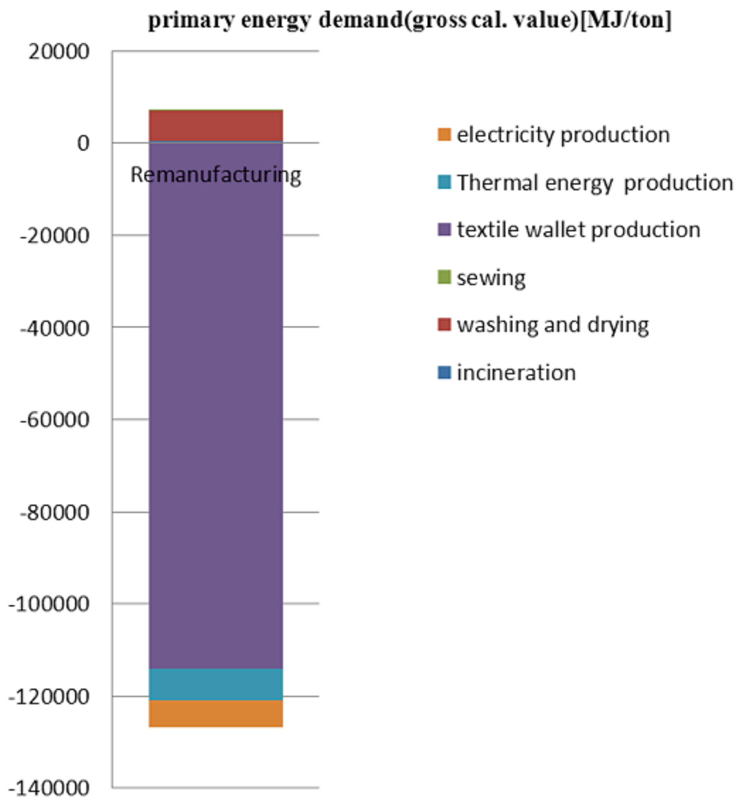


Figure 7. Primary energy demand in gross calorific value for the remanufacturing system

It should be taken into consideration that the inventory data for energy demand of the remanufacturing process originates from a small-scale case; More investigation is needed if the remanufacturing process will be applied in large scale. More details about the results of production of textile wallets from virgin raw material are provided in appendix D.

3.2.4 Sensitivity analysis

In order to make sure the processes are fairly compared, a number of analysis are needed to be performed. In this study, sensitivity analysis is performed with the aim of ensuring the reliability of the results. According to sensitivity analysis, crucial assumptions and uncertain data are varied for observing the effect on the results. The largest uncertainty factor relating to the remanufacturing process is the yield of the process, which is approximated to be 45%. This is a fairly rough estimation;the quality of collected textile waste is directly affecting the yield of the process. If considerable amounts of discarded textile consists of poor quality and torn down fabrics, the recovery rate of the process will certainly decrease. Consequently, a massive load of textile waste would be directed to incineration. By varying the yield of the process from 20% to 70%, the effects on the result of net global warming potential and primary energy demand are investigated.

Figure 8 shows the results in 3 bars, one with 20% as the lower extreme for the yield; one with the base case with a yield of 45% and one with 70% as the higher extreme for the yield.

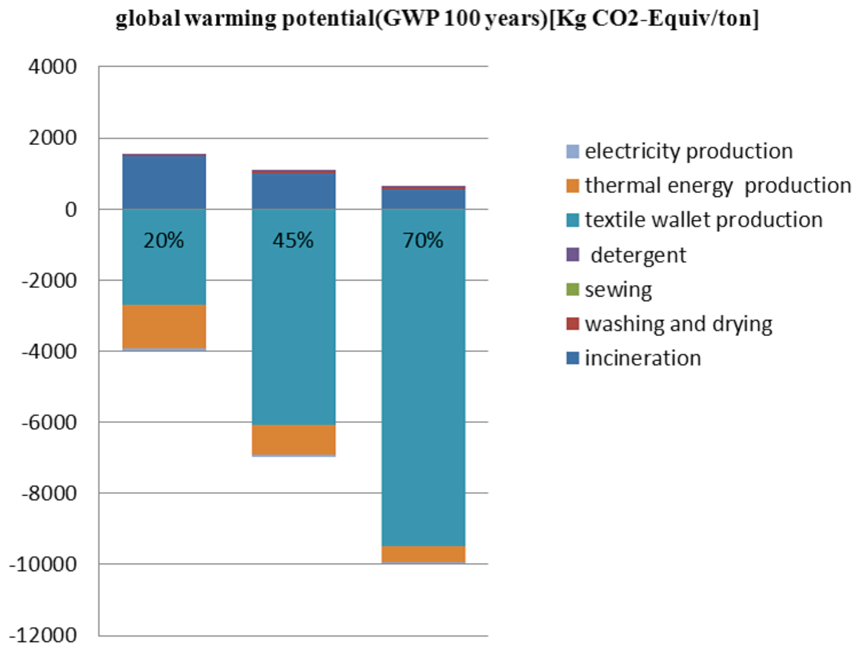


Figure 8. Emissions from the remanufacturing process with varied yield for the sorting of the waste input. The value of the yield in the low yield scenario is 20%, in the base case scenario it is 45% and for the high yield scenario it is 70%.

As can be seen in figure 8, by decreasing the yield of the sorting to 20%, the amount of textile waste sent to incineration will increase, therefore, the CO_2-equiv emissions will increase by 58%. By increasing the yield of the sorting, more textile wallets from recycled material are replacing textile wallets from virgin material. In other words, by increasing the value of the yield, less virgin textile would be produced. This shows that the recovery rate of the process has a substantial effect on the system performance.

The most significant contribution to global warming potential in all three cases is the production of textile wallets from virgin material.

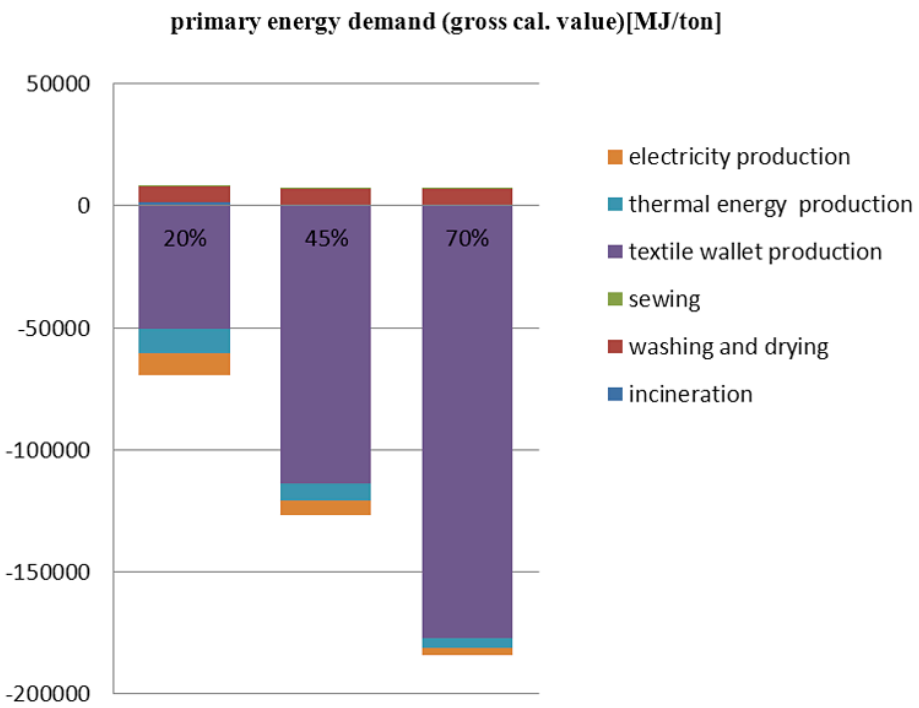


Figure 9. Primary energy usage of the remanufacturing process with varied yield in the sorting of waste input. The value of the yield in the low yield scenario is 20%, in the base case scenario it is 45% and in the high yield scenario it is 70%.

According to figure 9, as the yield of the process is reduced, more textile waste is sent to incineration, and more energy is produced as an alternative to external energy supply. On the other hand, by increasing the yield of the process, more textile wallet from recycled material is substituting virgin material, and as a result more energy will be saved by avoiding virgin production processes.

3.3 The Lyocell process

3.3.1 Process description

In the Lyocell process, N-methylmorpholine-N-oxide is mixed with the textile waste containing 50% cotton and 50% polyester. The solution of cellulose is then pumped through filters to separate the cellulosic solution from the polyester, which remains undissolved. The quality of the remaining polyester is assumed to be high enough, hence it is directed to spinning machines and, by twisting and extending the fibers, turned into yarns.

The solution of NMMO and cellulose, on the other hand, is forced through a showerhead spinners until long strings of fibers come out through small holes. The cellulosic yarns pass through a drying area, to evaporate water. It is estimated that 98% of the NMMO solvent is recovered and reused after the spinning step [5][18][22]. Finally, the residues from the whole process is sent to an incineration plant [5][18][19][20], see figure 10:

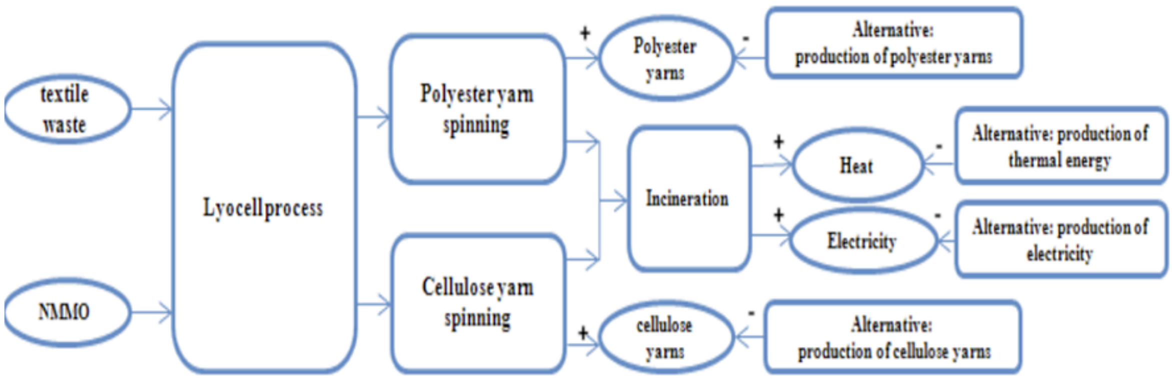


Figure 10. Scheme of the Lyocell process

The data set used for modeling the Lyocell process is as follows:

Table 3. Energy consumption in the Lyocell process

Process	Energy consumption	Reference
NMMO production	Electrical energy: 85×10^4 MJ/tonne of NMMO Thermal energy: 85×10^4 MJ/tonne of NMMO	[5]
Lyocell process	Electrical energy: 4 MJ/tonne of textile waste Thermal energy: 5000 MJ/tonne of textile waste	[5][22][24]
Polyester yarn spinning	Electrical energy: 12.076 MJ/ tonne of yarns	[15]
Cellulose yarn spinning	Electrical energy: 12.076 MJ/ tonne of yarns	[15]

Assumptions:

- According to Perepelkin *et al.* (2007) [19], the amount of required NMMO in the process falls between 0.01 - 0.05 kg/kg of cellulose thread. In order to avoid underestimation, the consumption of NMMO has been considered to be 0.05 kg/kg of cellulose in the textile.
- It is assumed that electricity is supplied by average Swedish electricity mix [23] and natural gas resources supply thermal energy [23].

3.3.2 System expansion

The aim of the system expansion is to calculate net avoided greenhouse gas emissions and primary energy usage. In the expanded system, alternative (conventional) processes of producing an equivalent amount of polyester and cellulose yarns, heat and electricity from virgin resources are included.

The virgin yarns manufacturing process includes production of polyester and cellulose fibers from virgin materials, seperately. Produced fibers will then be spun into yarns. Assuming that the process takes place in China, produced yarns need to be shipped to Sweden. During the process, electrical energy is supplied by average Chinese electricity mix and thermal energy is supplied by natural gas. The residues of the process are directed to landfill as it is the dominant waste management method in China.

The electrical energy produced from incineration will be utilized as replacement for average Swedish electricity mix [23]. In addition, thermal energy that is recovered from incineration will substitute thermal energy supplied from natural gas [23].

Data for modeling polyester and cellulose yarns production processes are according to Kalliala *et al.* (1999)[15] and Palamutcu *et al*. (2009) [17], respectively.

3.3.3 Results

The calculated results in this section represent the total performance of the Lyocell process in terms of global warming potential and primary energy usage.

In Figure 11, results of global warming potential per tonne of treated textile waste for the Lyocell process are presented. It can be seen that a significant contributor to global warming potential is the virgin production of cellulose and polyester yarns.

Furthermore, massive amounts of thermal energy (5000 MJ/tonne of textile waste) are required for the Lyocell step, which is therefore the second most significant contributor to the global warming potential.

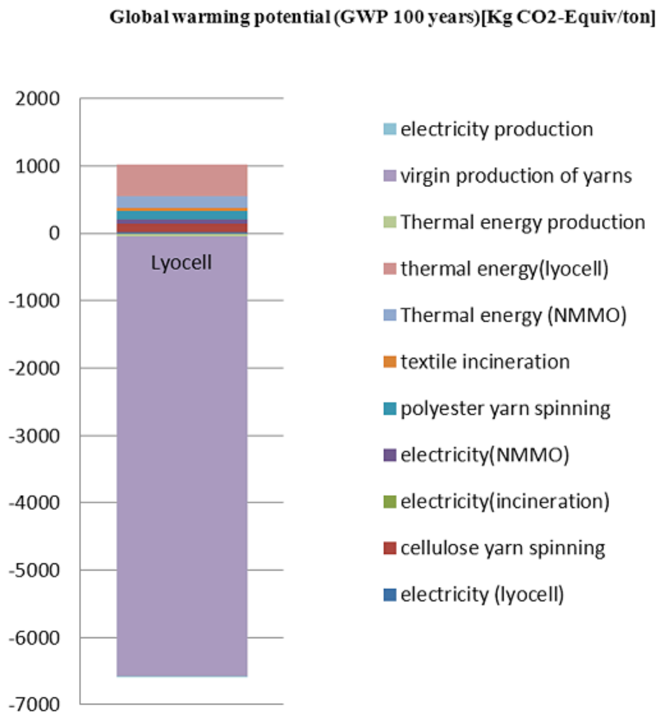


Figure 11. Global warming potential in kg CO_2-equivalent per tonne of textile waste for the Lyocell system

Figure 12 illustrates the total system performance of the Lyocell process from energy usage perspective. Considerable amounts of energy (nearly 135 GJ/tonne of textile waste) is saved by replacing virgin production of cellulose/polyester yarns with the Lyocell process.

In addition, the cellulose/polyester yarn spinning step, which requires electricity, has a significant role in the primary energy demand.

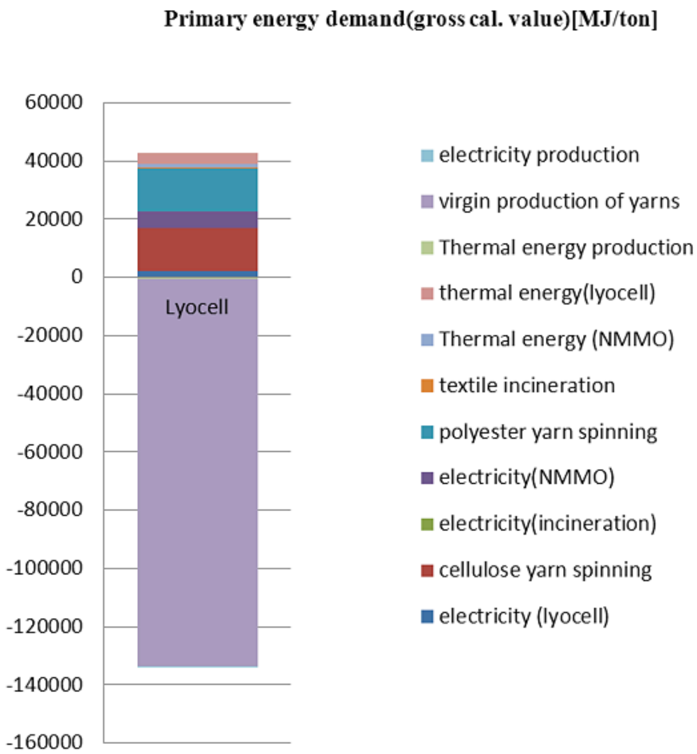


Figure 12. Primary energy demand in gross calorific value for the Lyocell system

3.3.4 Sensitivity analysis

In sensitivity analysis, data and assumptions with signficant influence on the results are identified.

The amount of thermal energy required for the Lyocell process is approximated to be 5000 MJ/tonne of textile waste. As the Lyocell process has not been tested in large scale, the data was derived from similar processes in industry [5][22][24]. In order to investigate the potential contribution of this step to the total performance of the system, the amount of required heat was varied in the range of (-/+) 50%.

Furthermore, in the base case, thermal energy is produced from natural gas, which is likely the long-term marginal heat source. The effect on the results from other possible alternatives needs to be investigated. Since the recycling techniques will assumingly be applied in Sweden, Swedish district heating [23] can be considered as an alternative for the thermal energy.

Figure 13 shows the results for the sensitivity analysis in 3 bars:

- Higher extreme: increasing required thermal energy by 50% in the Lyocell step.This is compensated for by an increased use of natural gas. Further details can be found in Appendix C.
- Base case as the reference Lyocell process.
- Lower extreme: reducing required thermal energy by 50% in the Lyocell step. In order to further reduce the global warming potential impact, the thermal energy used by the Lyocell process was considered to be supplied by Swedish average district heating [23]. Further details regarding selection of the extremes can be found in Appendix C.

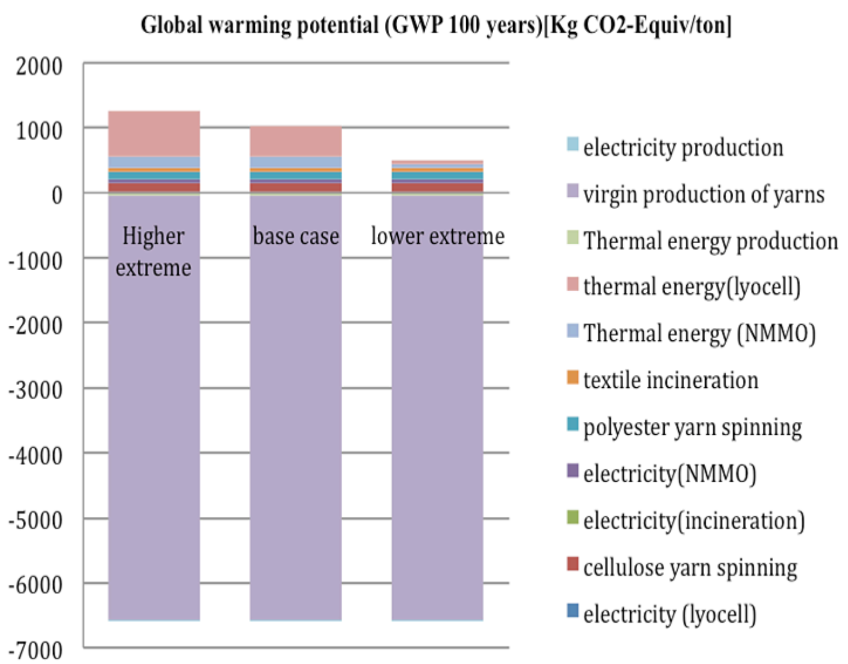


Figure 13. Emissions from the Lyocell process (varied thermal energy for the Lyocell step (-/+ 50%), varied source of thermal energy: Natural gas in two first bars and Swedish district heating in last bar)

Comparing the higher extreme with the base case shows that by increasing the amount of thermal energy needed for Lyocell step, CO_2-emissions increase by approximately 3%, see figure 13.

According to the hypothetical environmental improvement in the lower extreme case, the global warming potential is reduced by 7%.

Figure 14 shows the result from the sensitivity analysis in 3 bars:

- Higher extreme: increasing required thermal energy by 50% in the Lyocell step.This is compensated for by use of Swedish district heating system as the source of thermal energy.
- Base case as the reference Lyocell process.
- Lower extreme: reducing required thermal energy by 50% in the Lyocell step. In order to further reduce the primary energy demand, the thermal energy used by the Lyocell process was considered to be supplied by natural gas. Further details relating to choosing the extremes can be found in Appendix C.

reducing required thermal energy by 50% in the Lyocell step. In order to further reduce the potential impact, the thermal energy used by the Lyocell process was considered to be supplied by Swedish average district heating [23]. Further details regarding selection of the extremes can be found in Appendix C.

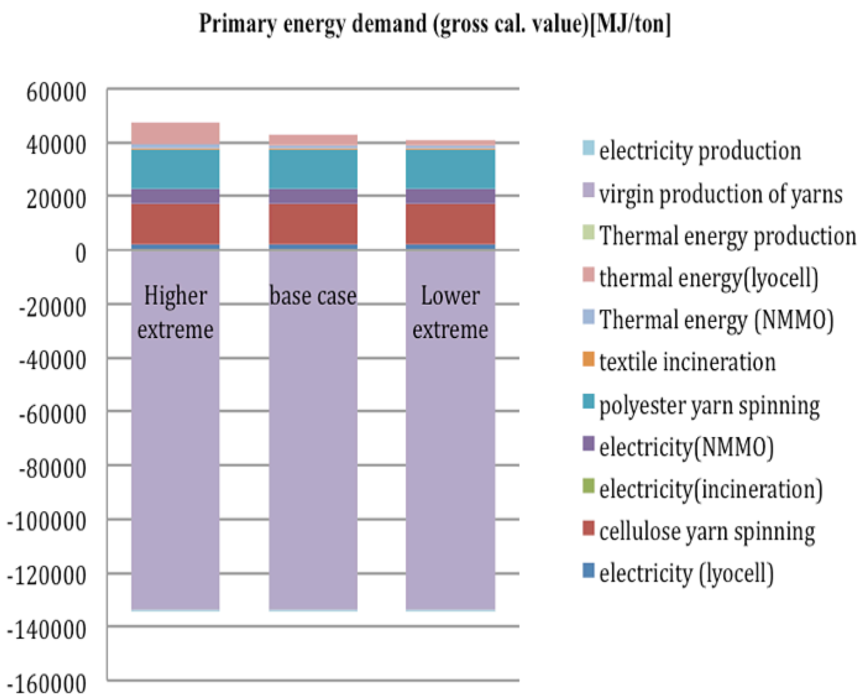


Figure 14. Primary energy usage of the Lyocell process (varied thermal energy for the Lyocell step (-/+ 50%), varied source of thermal energy: Swedish district heating in first bar and Natural gas in last two bars)

Figure 14 illustrates that changing the source of thermal energy from natural gas to district heating does not have a significant effect on the net results.

3.4. Patagonia process

3.4.1 Process description

According to the process flow chart in Figure 15, 100% polyester discarded garments and fabrics are first separated manually from the rest of the textile waste. They are then cut into smaller pieces and further broken down until only small granules remain. A chemical reaction is applied to break the granules down into molecules of DMT (dimethyl terephthalate) that is the intermediate chemical for PET (polyethylene terephthalate) production. Subsequently, DMT is chemically treated and polymerized to produce polyester granules, which will be spun into polyester yarns. The residue of the spinning yarn process plus the residue from the sorting step is directed to an incineration plant [8].

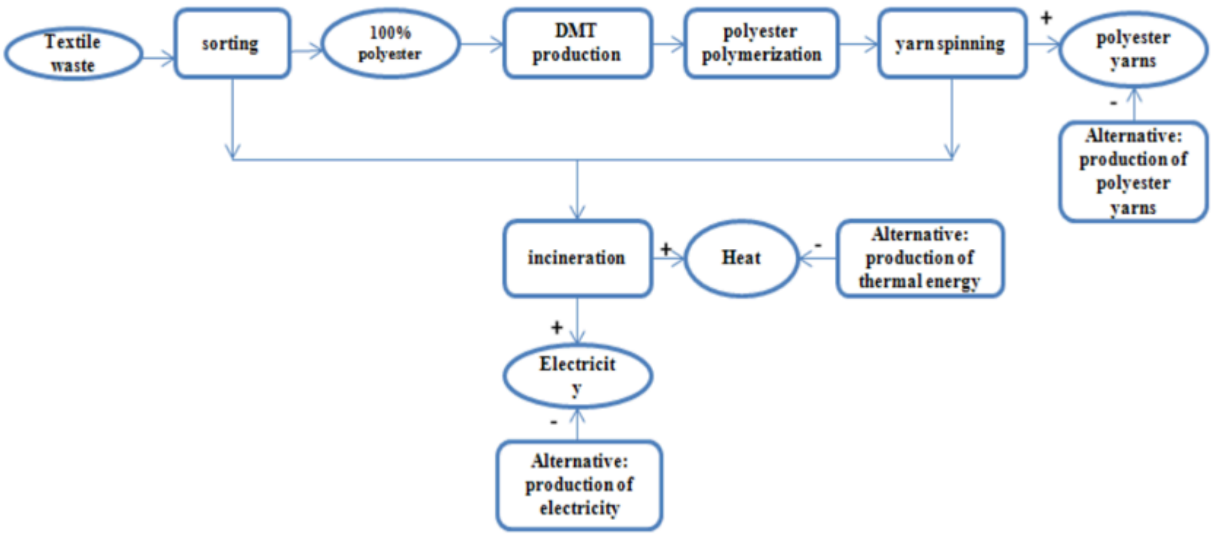


Figure 15. Process scheme of the Patagonia process

The data set used for the modeling is as follows:

Table 4. Energy consumption in the Patagonia process

Process	Energy consumption	Reference
DMT production (from textile waste)	Thermal energy: 11891 MJ/tonne of DMT	[8]
Polyester polymerization	Electric energy: 3300MJ/tonne of polyester Thermal energy: 3800 MJ/tonne of polyester	[25][26]
Polyester yarn spinning	12.076 MJ/ tonne of yarns	[15]

Assumptions:

- It is assumed that half of the inlet stream consists of 100% polyester textile waste.
- According to the report by Patagonia Inc. [8], the rate of conversion during DMT production from polyester textile waste is assumed to be 90%, thus 909 kg of DMT is produced from 1 tonne of used textiles.
- The residue of the spinning process, assumingly 3% of the weight of the polyester fibers, [15] is sent to incineration.

- It is assumed that electricity is supplied by average Swedish electricity mix [23] and natural gas resources supply thermal energy [23].

3.4.2 System expansion

System expansion is needed for calculating the net avoided greenhouse gas emissions and primary energy usage. In the expanded system, alternative processes of producing an equivalent amount of polyester yarns, heat and electricity from virgin resources are included.

In the virgin production process, DMT is produced using virgin materials and polymerized to polyester granules [8]. The polymerized granules will then be spun to polyester yarns [8].

Furthermore, the electrical energy produced from incineration will be utilized as a replacement for average Swedish electricity mix [23]. Thermal energy recovered from incineration will substitute thermal energy supplied from natural gas [23].

3.4.3 Results

The results in this section represent the total performance of the Patagonia process in terms of global warming potential and primary energy usage.

Results relating to global warming potential per tonne of treated textile waste during from the Patagonia system are presented in Figure 16. The most significant contributor to global warming potential is the virgin production of DMT, which is, in fact, avoided by applying the Patagonia process.

Moreover, as the rest of the 50% textile waste is sent to incineration, it has a considerable share in the global warming potential. On the other hand, significant amount of thermal energy that is recovered from incineration will substitute thermal energy supplied from natural gas .This results in some positive effect on global warming potential.

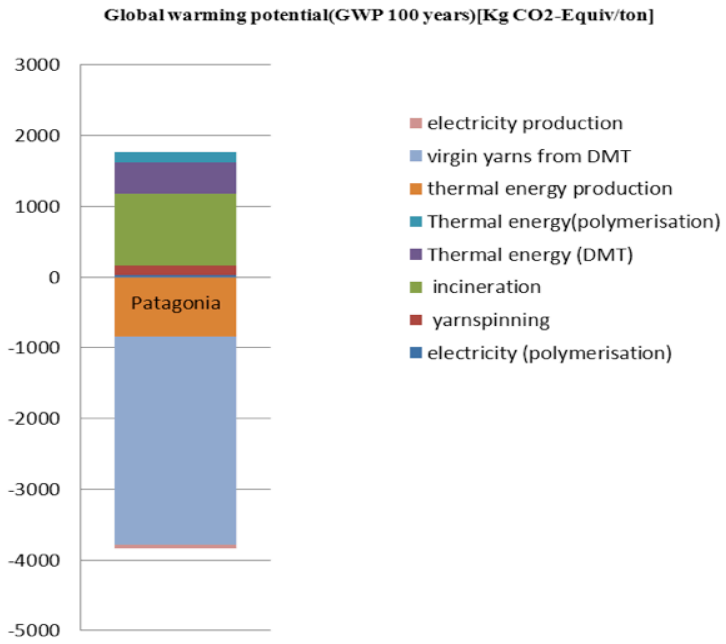


Figure 16: Global warming potential in kg CO_2-equivalent per tonne of textile waste for the Patagonia system

The total performance of the Patagonia process can also be viewed in energy terms, see Figure 17. In virgin production of DMT, extraction and transportation of oil in order to manufacture DMT is required [8]. As a result, production of DMT from virgin materials demands approximately 84% more energy than manufacturing DMT from recycled materials [8]. By applying the Patagonia process, the mentioned amount of energy is saved as the production of an equivalent amount of DMT out of virgin materials is prevented.

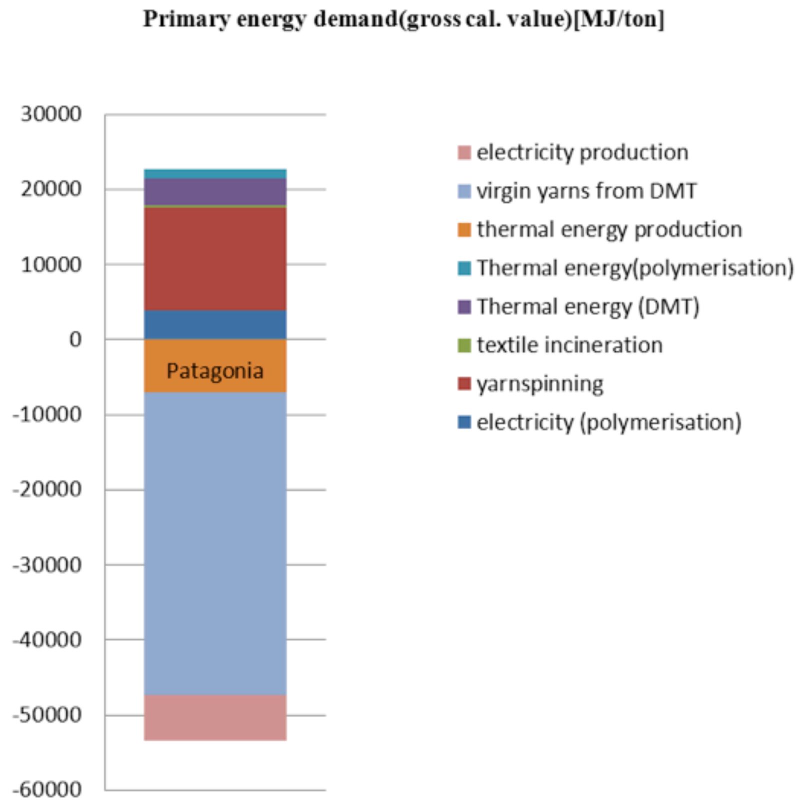


Figure 17: Primary energy demand in gross calorific value for the Patagonia process

3.4.4 Sensitivity analysis

In sensitivity analysis, data and assumptions with signficant influence on the results are identified.

The amount of thermal energy required in the polymerization step is based on a rough estimated using the Eco-profile report [25][26]. In order to investigate how the amount of required heat affects the performance of the system, the value is varied in the range of (-/+) 50%.

Furthermore, in the base case, thermal energy is produced from natural gas, which is likely the long-term marginal heat source. The effect on the results from other possible alternatives needs to be investigated. Since the recycling techniques will assumingly be applied in Sweden, Swedish district heating [23] can be considered as an alternative to thermal energy.

Global warming potential

Figure 18 shows results of the sensitivity analysis in 3 bars:

- Higher extreme: increasing required thermal energy by 50% in the polymerization step.This is compensated for by use of natural gas as the source of thermal energy.
- Base case as the reference Patagonia process.
- Lower extreme: reducing required thermal energy by 50% in the polymerization step. In order to further reduce the global warming potential impact , the thermal energy used by the Patagonia process was considered to be supplied by Swedish district heating. Further details relating to choosing the extremes can be found in Appendix C.

According to Figure 18, the heat demand for the polymerization step has an insignificant role in the global warming potential of the system. Furthermore, by modifying the environmental performance of the whole system in a lower extreme, the global warming potential is reduced only by approximately 6%.

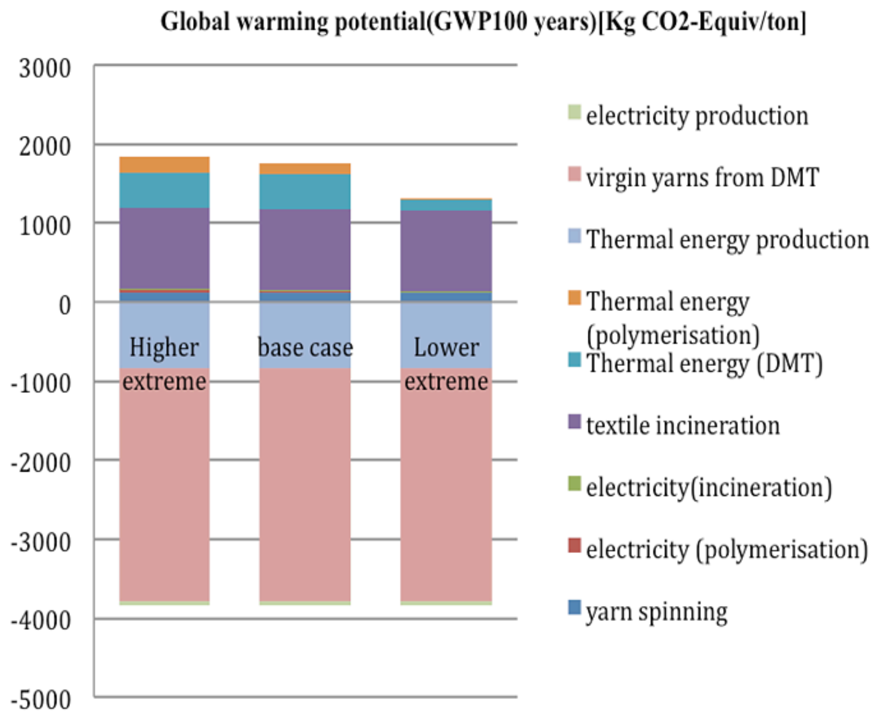


Figure 18. Emissions from the Patagonia process (varied thermal energy for polymerization step (-/+ 50%), varied source of thermal energy: Natural gas in two first bars and Swedish district heating system in last bar)

Primary energy demand

Figure 19 shows the result in 3 bars:

- Higher extreme: increasing required thermal energy by 50% in the polymerization step. This is compensated for by use of Swedish district heating system as the source od thermal energy.
- Base case as the reference Patagonia process.
- Lower extreme: reducing required thermal energy by 50% in the polymerization step. In order to further reduce the primary energy demand, the thermal energy used by the Patagonia process was considered to be supplied by natural gas. Further details relating to choosing the extremes can be found in Appendix C.

As presented in Figure 19, reduction of the energy demand for polymerization and using natural gas as the heat resource, would result in a reduction of the total energy demand by 13%.

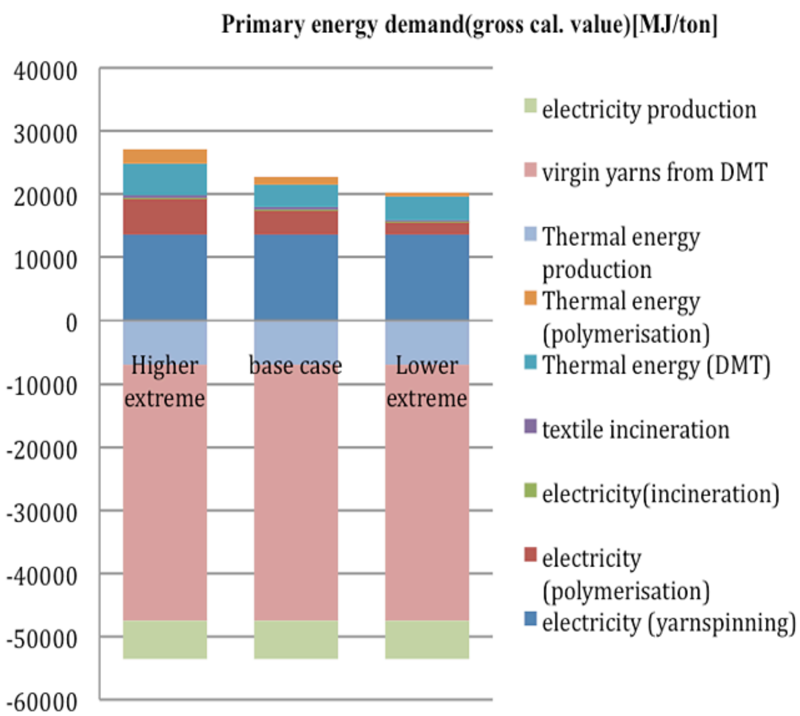


Figure 19. Primary energy usage of the Patagonia process (varied thermal energy for polymerisation step (-/+ 50%), varied source of thermal energy: Swedish district heating system in first bar and Natural gas in last two bars)

3.5 Comparison of the scenarios

In order to specify the most environmentally beneficial textile recycling scenario, comparison of the results from both aspects of global warming potential and primary energy demand is needed.

Table 5 shows a comparison between the 3 studied recycling techniques with the incineration reference case, from the global warming potential and primary energy usage aspects.

Table 5. Results for the total system performance (kg CO_2-Equiv/ tonne of textile waste)

System	Global warming potential (CML 2007)
Remanufacturing process	-5900
Lyocell process	-5560
Patagonia process	-2075
Textile incineration	230

As shown in Figure 20, all three suggested recycling methods are preferable to incineration from global warming potential perspective. The black lines on each bar illustrates the sensitivity analyses performed for each case.

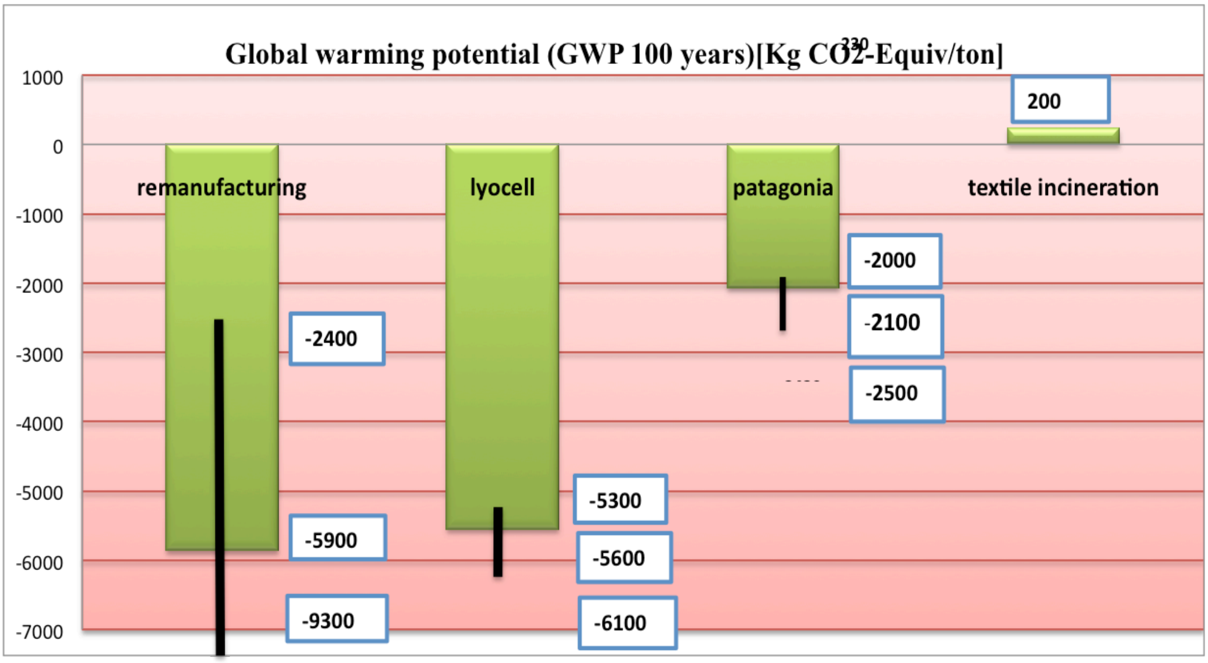


Figure 20. Total global warming potential of textile recycling techniques

Figure 20 illustrates that the global warming potential has its lowest value for the remanufacturing process. The main factor relating to global warming potential in remanufacturing is the yield of the initial sorting. As mentioned before, the whole process of remanufacturing is applied in small-scale, therefore, here the amount of required electrical energy for washing, drying and sewing steps are for a small-scale case. By increasing the yield of the process, the amount of residues sent to incineration will decrease and consequently, the global warming potential will be reduced as well.

The Patagonia process has a higher global warming potential than the other two suggested recycling options. Since this method is applicable for textile waste consisting only of polyester, only half of the inlet stream can be recycled by the Patagonia method and the remaining textile waste would be incinerated. The impact of incineration on global warming potential is significant.

Table 6 shows the results for the primary energy demand from renewable and non-renewable resources for each recycling technique and for incineration.

Table 6. Results for the primary energy demand (MJ/ tonne of textile waste)

System	**Primary energy demand**
Lyocell scenario	-91,100
Patagonia scenario	-30,700
Remanufacturing scenario	-119,700
Textile incineration	-22,607

Figure 21 illustrates that, from energy perspective, all three recycling techniques are more preferable than incineration. This is mainly due to the amount of energy saved by averting energy-intensive manufacturing processes of virgin materials in each case.

Among the presented recycling techniques, the remanufacturing process is the most preferable option (disregarding the potential variation in yield of the process). It should be noted that energy usage for alternative production of textile wallets from virgin material has a significant effect on the total primary energy usage in this case.

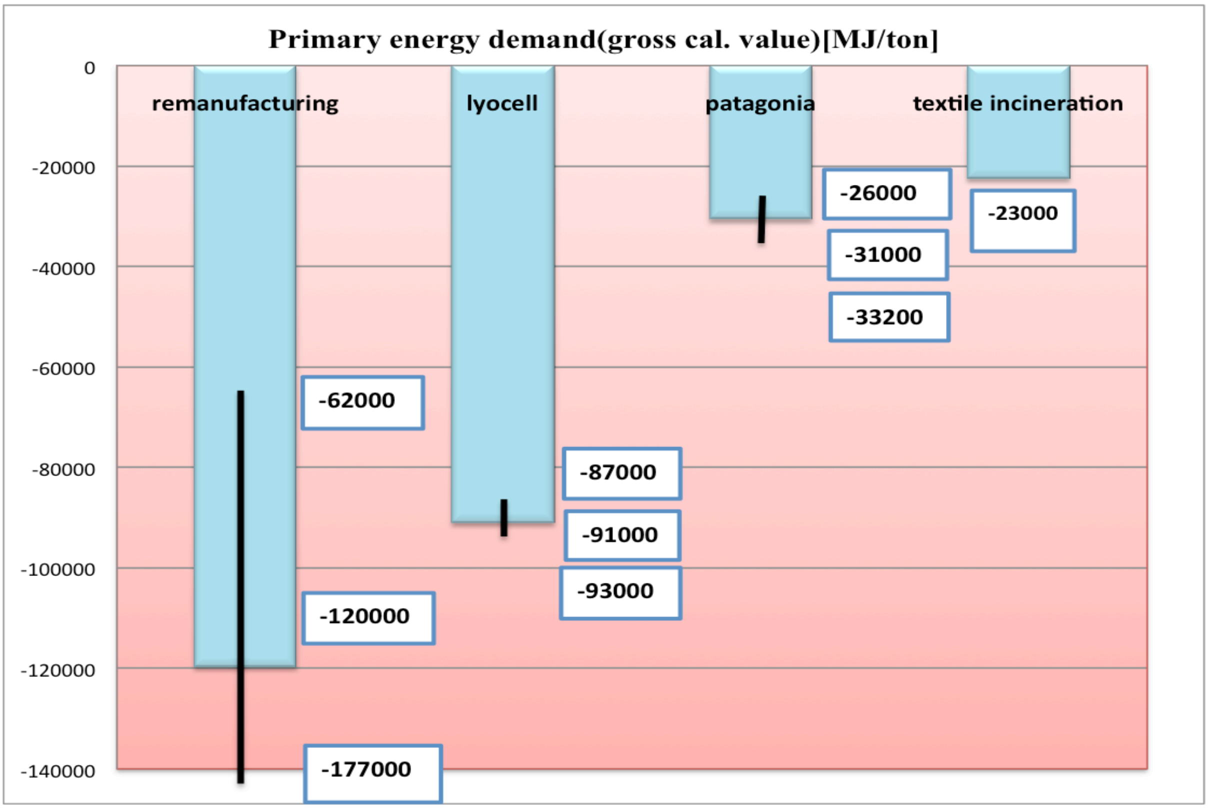


Figure 21. Net primary energy demand – comparison between the four systems

4. Integration of the scenarios

In this section, the three recycling techniques are combined together to assess the net global warming potential and net primary energy demand for treatment of the net flow of textile waste in Sweden annually. The results are compared with incineration as the reference case for the same functional unit.

It should be taken into consideration that the technical and economical feasibility of the processes need further investigation and the results presented in this study can be used only as a preliminary environmental assessment.

4.1 Methodology and system description

4.1.1 Process description

Referring to Figure 22, collected textile waste is initially sent to remanufacturing. The whole inlet flow is washed and dried and reusable parts of the waste with high quality are separated manually for the sewing stage. Residues of the sewing step plus the amount of unused textile are collected and directed to the Lyocell process. In the next step, NMMO separates cellulosic and polyester fibers from each other by dissolving cellulose. Cellulosic yarns are spun from the solution of NMMO and cellulose. The polyester residues are sent to the Patagonia process. In the Patagonia phase, collected polyester residues are cut into smaller granules and broken down to DMT molecules by applying chemical reactions. Afterwards, DMT can be used as an intermediate material for polymerizing to PET. Polyester yarns are spun from the PET granules in the next stage. Finally, the residues of the whole process are collected and sent to an incineration plant (red arrows in Figure 22).

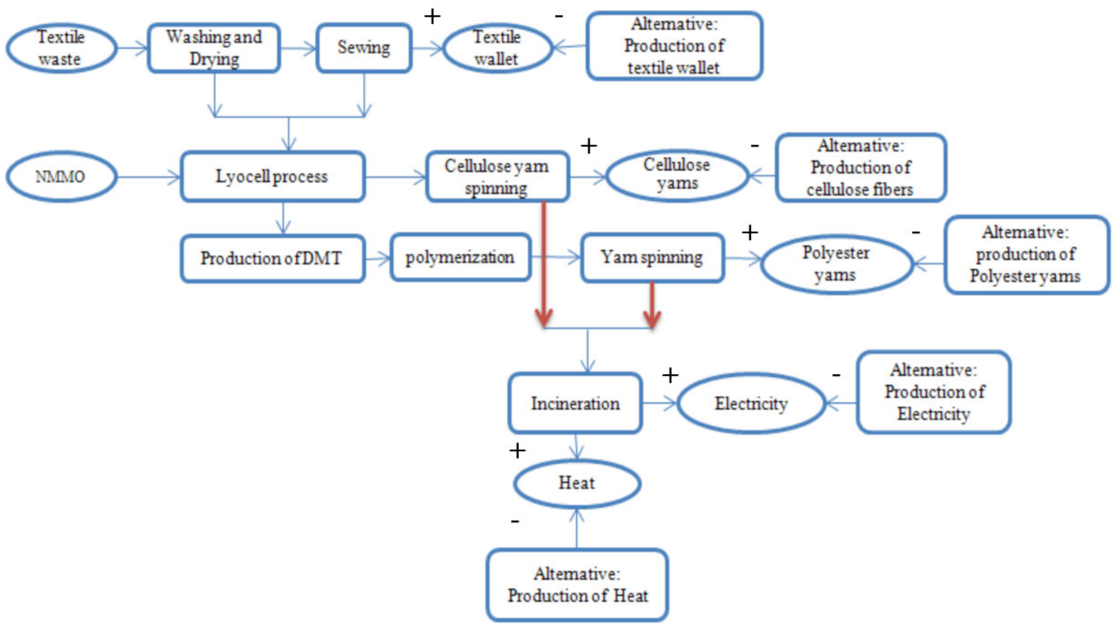


Figure 22. Integrated process scheme, combining the recycling techniques

4.1.2 Functional unit

As the goal of this section is to compare the environmental impacts of the combined scenarios with the existing treatment system in Sweden, the functional unit is chosen as *treatment of the total intake of household textile waste in Sweden*, which equals to 1.41×10^{8} *kg annually*. Average textile waste production in Sweden is 15 kg per person annually [27] and the population of Sweden is estimated to be 9.4 million people [28].

The results from the integrated system are compared with the base case, which is incineration of the whole collected household textile waste in Sweden, annually.

4.1.3 Assumptions and delimitations

- The whole integrated system is assumed to be performed in one site; hence no transportation is considered between steps of the process.
- All the steps of the recycling process operates in Sweden, therefore the electrical energy supply is considered to be average Swedish electricity mix.
- Manufacturing processes for textile wallets and cellulose/polyester yarns from virgin raw materials are assumed to take place in China, therefore average Chinese electricity mix provides the required electricity for these processes.
- Environmental impacts due to shipment from China to Sweden are taken into account.
- The thermal energy supply for the whole process is natural gas.
- The impact categories are limited to global warming potential due to carbon dioxide, methane and nitrous oxide emissions and primary energy demand of the system.

4.1.4 Data quality

As there is no textile recycling plant currently existing in Sweden, most of the data is taken from literature reviews from other countries or are assumptions.

The data related to the reference case (incineration) is based on the SWEA model by Palm *et al*. (2010) [12], based on Björklund *et al*. (2009) [13].

Since most of the data is based on assumptions, this study cannot indicate the properties of any textile recycling plants in particular, but can provide preliminary results for the individual technologies, for comparisons of them, and for integration of them in a combined system.

4.2 Results

The results, characterized using the CML method for global warming potential and primary (non-renewable and renewable) energy for energy, are presented in two sections. The first part indicates the environmental performance of the system by illustrating the share of each step in the global warming potential and in the primary energy usage. In the second part, the net environmental performance of the integrated system is compared with the base case scenario: incineration of the textile waste.

4.2.1 Contribution of different steps to total results

The results for global warming potential of the integrated system are shown in Figure 23. The first four positive green bars present the global warming potential due to the recycling processes. Green bars with negative value show the amount of avoided emissions due to system expansions when products from the recycling processes replace other means of production of heat, electricity, wallets and yarns. The total global warming potential of the system is shown in dark green color.

The most significant contributor to global warming potential is production of textile wallets from virgin raw material.

The value of the net global warming of the process is negative, which means that the amount of avoided CO_2 emissions due to this scenario is higher than the emissions caused by the process. As a result, the scenario is in fact environmentally beneficial from a global warming potential perspective.

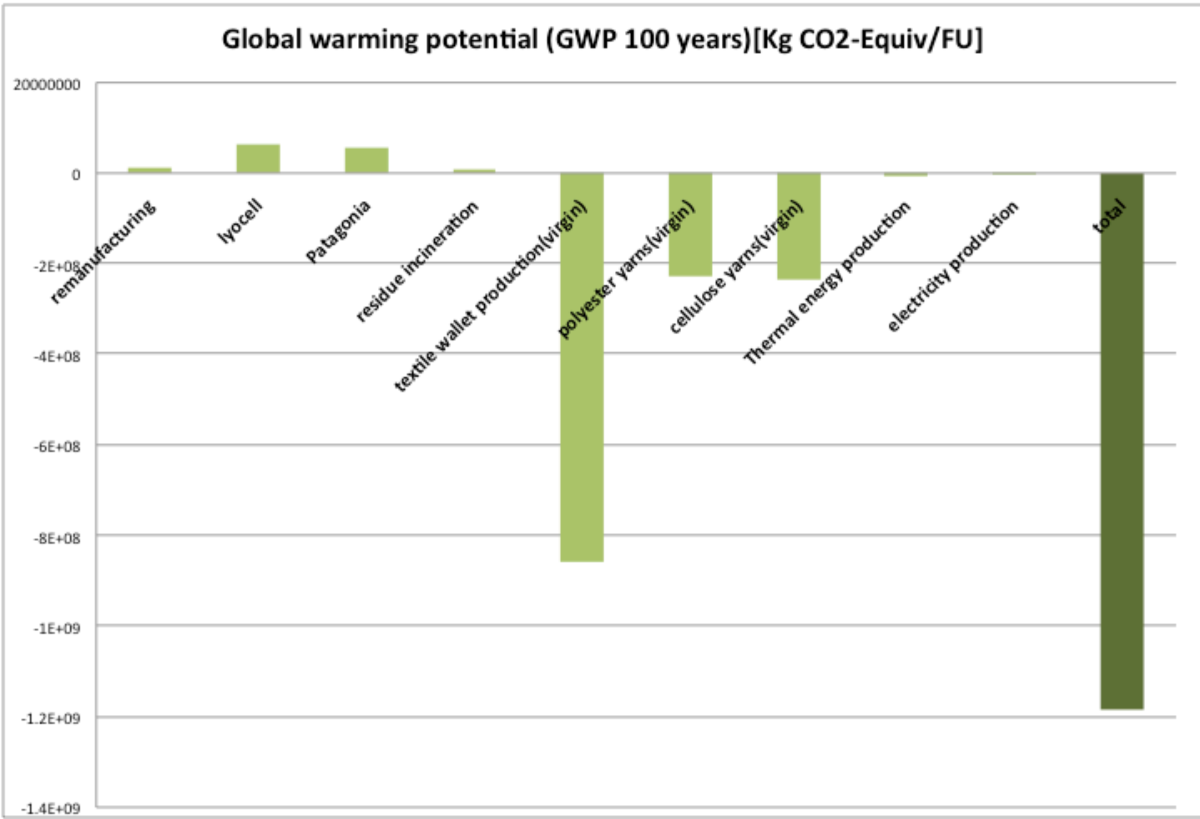


Figure 23. Global warming potential in kg CO_2-equivalent per functional unit for the different steps of the integrated scenario

The results relating to primary energy usage of the integrated system are shown in Figure 24. The first light blue bars present the primary energy demand of the recycling steps. The total primary energy demand of the system is shown in dark blue color.

It can be concluded that a considerable amount of energy is saved when virgin production processes are replaced by various recycling techniques.

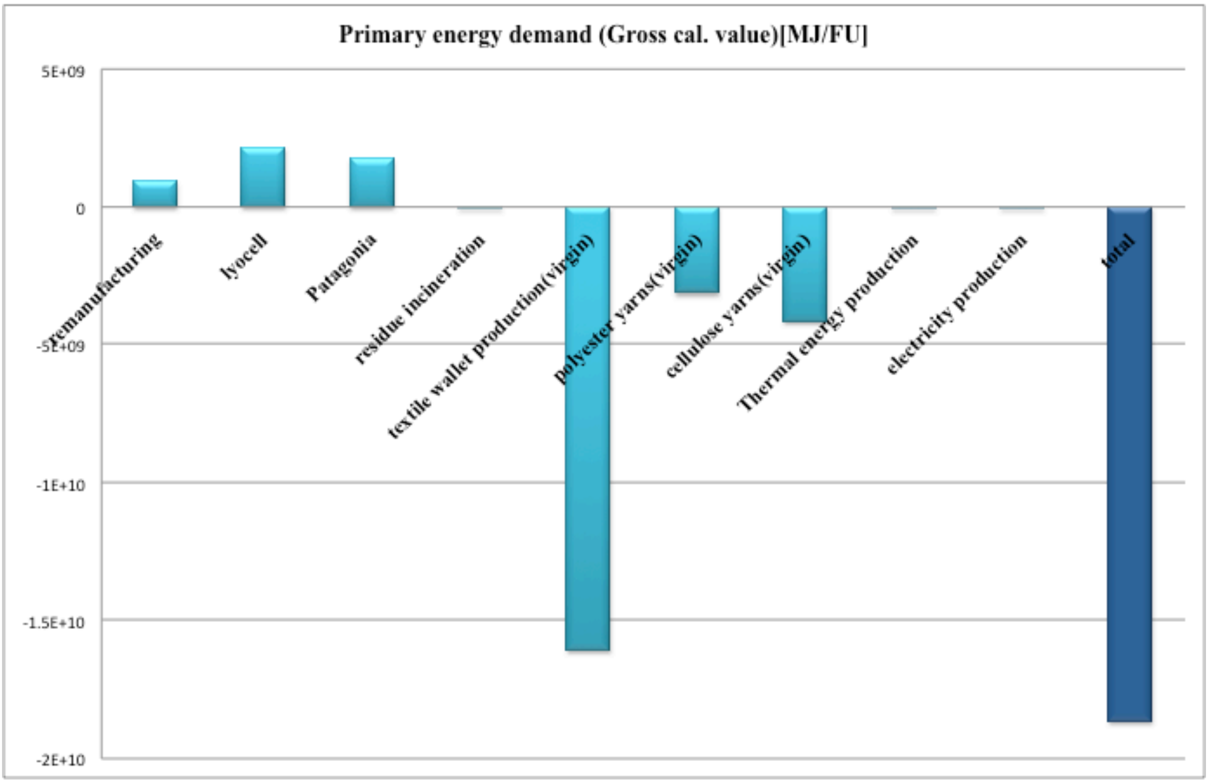


Figure 24. Primary energy demand in gross calorific value per functional unit for the different steps of the integrated scenario

4.2.2 Comparison to reference case

According to Figure 25, the advantages of applying the recycling techniques instead of the existing method in Sweden become obvious. Although the possibility of constructing the whole system is uncertain, the results show that the proposed plan is more beneficial from environmental point of view compared to incineration.

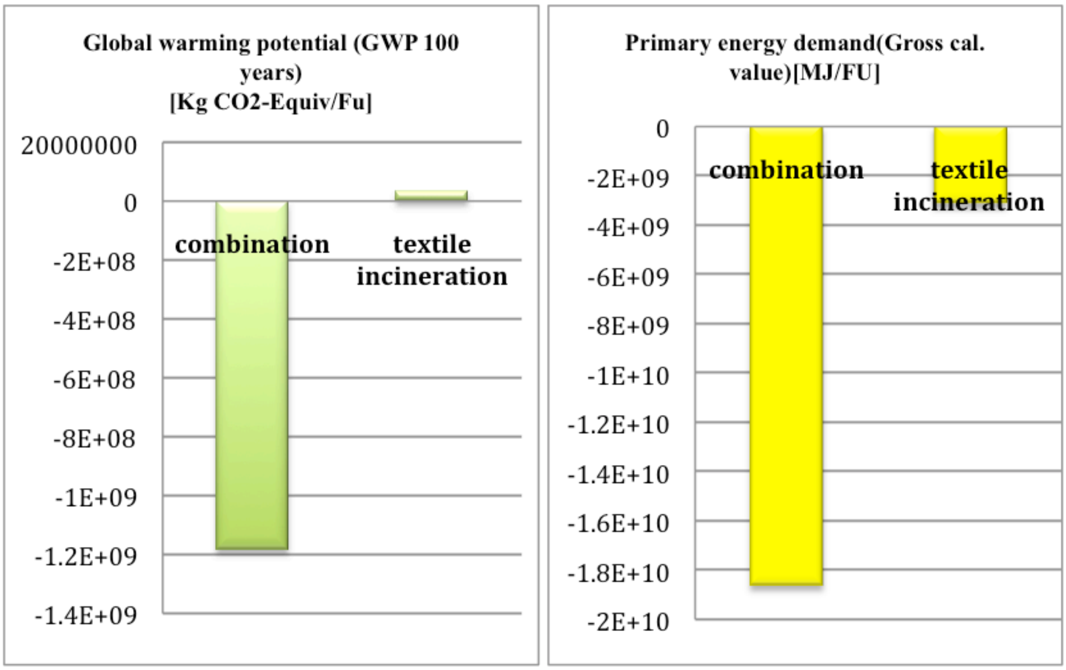


Figure 25. Total environmental system performance of the integrated system compared to incineration - global warming potential and primary energy usage

Based on the report provided by Swedish environmental protection agency, greenhouse gases emissions, directly relating to consumption plus international transports in Sweden, equaled to approximately 95 million tonnes of CO_2-equiv, in 2003 [29]. By applying the comined textile recycling techniques, approximately 1.2 million tonnes of CO_2-Equiv will be saved annually.This means that applying the integrated textile recycling techniques can reduce the total average global warming potential in Sweden by 1.26%.

5. Discussion and suggestions

Textile waste normally includes different types of fibers with different colors. It is often fairly complicated to separate textile fibers from each other. Perhaps due to technical and economical barriers, there is currently no existing recycling of textile waste in Sweden. However, certain simplifications and assumptions, which were made in this thesis, allowed the environmental performance of three different textile recycling techniques to be investigated. It should be noted that achieved results are just applicable for a preliminary environmental assessment, since most of the data was either based on assumptions, derived from foreign literature or approximated with data from similar processes.

Despite the difference in type of products from each recycling technique, obtained results of global warming potential and primary energy are comparable due to the fact that system expansion was made in each case.

Based on the results, the remanufacturing process has the lowest impact on in terms of global warming potential and primary energy demand. It must be said that choosing the ultimate environmentally preferred system is not feasible at this point due to uncertainties in assumptions. For example, more investigation is needed to increase the accuracy for the chosen value for the yield of the initial sorting in the remanufacturing process. As mentioned before, the results of both global warming potential and primary energy usage are directly dependant on yield, which in turn is highly dependant on the quality of the textile waste inflow.

As stated in this study, data used for energy usage in each step in the remanufacturing process is based on approximations for a small-scale plant. Furthermore, the alternative production of textile wallet from virgin material is assumed to take place in China. Hence, in order to select the most environmentally beneficial recycling techniques, other choices with different geographical boundaries need to be investigated.

In all three recycling cases, the global warming potential and primary energy usage of the processes is directly dependent on the virgin production alternatives. Based on the results for both the Lyocell and the remanufacturing processes, production of virgin cellulose/polyester fibers are energy-intensive processes. Replacing products from these two processes with products of the same kind from virgin raw material results in considerable savings in greenhouse gas emissions and primary energy usage.

Different thermal energy scenarios do not show a large impact on system performance for neither the Patagonia nor the Lyocell process. In comparison with incineration and disregarding the technical feasibility, the integration of the cases does provide environmental benefits from both global warming potential and energy usage perspective.

There are simplifications in the models that have not been analyzed. Firstly, it has been assumed that household textile waste consists of 50% cellulose and 50% polyester. By this assumption, any obstacles due to separation and sorting processes are ignored. More investigation needs to be done in order to find suitable recycling techniques for different types of textiles and textile waste mixes.

This study has focused on global warming potential and primary energy usage, but in order to obtain more thorough results, other environmental categories such as toxicity or water usage should be included in the calculations. Moreover, further investigation is needed for the technical and economical feasibility for both the recycling techniques separatelty and for the integrated process.

References

[1] Wang, Y., 2006, *Recycling in textile*, Woodhead publishing Ltd., Cambridge

[2] Palm, D., (2011), *Improved waste management of textiles*, IVL Swedish Environmental research institute Ltd., [online], Available at:

Http://www.ivl.se/download/18.7df4c4e812d2da6a416800080103/B1976.pdf, (Accessed August 2011)

[3] Fletcher, K., (2008), *Sustainable fashion and textiles: design journeys*, Earth scan, London

[4] Oakdende Hollins, (2009), *Maximizing reuse and recycling of UK clothing and textiles*, Oakdende Hollins Ltd, [online], Available at:

http://www.oakdenehollins.co.uk/pdf/defra_173_summary_issue_4.pdf, (Accessed August 2011)

[5] Shen, L., Patel, M., (2010), *Life cycle assessment of man-made cellulose fibers*, Lenzing Berichte, 88 (2010), pp. 1- 59.

[6] Lyocell, [online], Available at: http://en.wikipedia.org/wiki/Lyocell, (Accessed August 2011)

[7] Jahanipour, A., Karimi, K., Taherzadeh, M., (2010), *A novel process for ethanol or biogas production from cellulose in blended-fibers waste textiles*, Waste management magazine, Volume 30, pp. 2504-2509

[8] Patagonia Inc., (2011), *Patagonia´s common Treads Garment Recycling Program: A Detailed Analysis*, [online], Available at:

http://www.patagonia.com/pdf/en_US/common_threads_whitepaper.pdf, (Acessed August 2011)

[9] Baumann, H. Tillmann, A.M, (2004), *The Hitchhikers Guide to LCA*, Studentlitteratur. Göteborg

[10] GaBi software, [online], Available at:

http://www.gabi-software.com/index.php?id=85&L=31&redirect=1, (Acessed August 2011)

[11] Global warming potential, [online], Available at:

http://en.wikipedia.org/wiki/Global-warming_potential, (Accessed August 2011)

[12] Palm, D., Ljunggren Söderman, M., (2010), Bearbetning och beräkning av data från modellen SWEA, [In English: Processing and calculation of data from the SWEA model], Swedish Waste Management

[13] Björklund A., Eriksoson, O., Ljunggren Söderman, M., (2009), LCA of policy instruments for sustainable waste management

[14] P&G, (2006), *Comparative life cycle assessment of Ariel "Actif a froid" a laundry detergetns that allows to wash at colder wash with previous laundry detergents*, Proctor and Gamble, [online],

Available at:http://www.scienceinthebox.com/en_UK/pdf/Ariel_Actif_a_Froid_LCA_report_Nov 2006.pdf, (Accessed August 2011).

[15] Kalliala, E., Nousiainen, (1999), *Life cycle assessment – Environmental profile of cotton and polyester/cotton fabrics*, AUTEX research journal, Volume 1, pp. 8-20.

[16] Kalliala, E., Talvenmaa, P., (2000). *Environmental profile of textile wet processing in Finland*, Journal of cleaner production, Volume 8, pp. 143-154

[17] Palamutcu, S., (2010), *Electric energy consumption in the cotton textile processing stages*, Energy magazine, Volume 35, pp. 2945-2952.

[18] Eichinger D., Eibl, M., (1995), *Lenzing Lyocell - An interesting cellulose fiber for the textile industry*, Lenzinger Berichte, [online], Available at:

http://www.lenzing.com/fileadmin/template/pdf/konzern/lenzinger_berichte/ausgabe_75_1996/LB_1996_09_Eichinger.pdf. (Accessed August 2011)

[19] Perepelkin, K. E., (2007), *Lyocell fibers based on direct dissolution of cellulose in N-Methylmorpholine N-oxide: development and prospect*, Fiber chemistry, Volume 39, pp. 163-172.

[20] Borbley, E., (2008), *Lyocell: The new generation of regenerated cellulose*, Acta polytechnic Hungrica, Volume 5, pp. 11-18.

[21] Shen, L., Patel, M. (2008), *life cycle assessment of Polysaccharide materials: a review*, Journals of polymers and Environment, Volume 16, pp. 154-167.

[22] European Commission directorate, (2006), Integrated pollution prevention and control, *Reference document on best available techniques in the production of polymers*, European Commission directorate-General JRC joint research centre: institute for prospective technological studies

[23] PE international, GaBi professional database

[24] Rydberg, T., Frankenhaeuser, M., (1995), *LCA of the Tetra brik milk package system: product and process development options for improved environmental performance*, Chalmers Industriteknik, Sweden

[25] Infante, F., Guadalup, A., (2011), Chemical process for recycling polyethylene terephthalate (PET) waste, United state Patent

[26] Axel, L., Guegrich,J., (2010), *Eco profiles of the European plastic industry: Polyethylene Terephthalate(PET) (Bottle grade)*, Institut für Energie- und Umweltforschung Heidelberg GmbH, [online], Available at:

http://www.plasticseurope.org/plastics-sustainability/eco-profiles/browse-by-flowchart.aspx, (Accessed August 2011)

[27] SEPA, (2011), *Kartläggning av mängder och flöden av textilavfal,* [In English: Mapping of amount and flows of textile waste], Swedish Environmental Protection Agency, Stockholm

[28] Sweden, [online], Available at: http://en.wikipedia.org/wiki/Sweden, (Accessed August 2011)

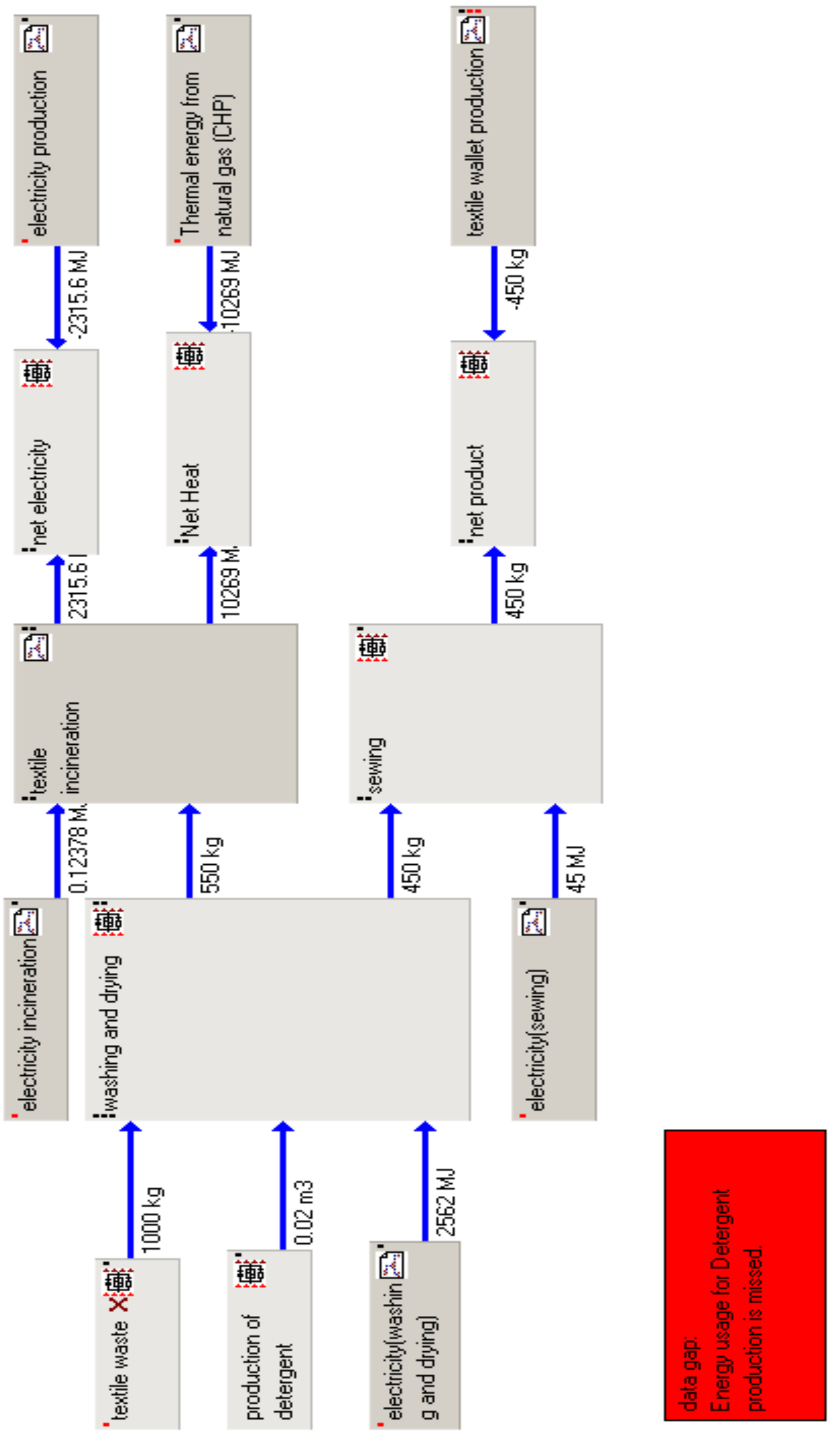
[29] SEPA, (2011), *Swedish consumption and the global environment*, Swedish environmental protection agency, Stockholm

[30] Shinshemer, P., Grout, C., (2004), *Comparison of Energy and Water Use of Five Garment Care Technologies: Evaluation the Potential for an Electricity Rebate Program for Professional Wet Cleaning*, UEPI papers, [online], Available at:

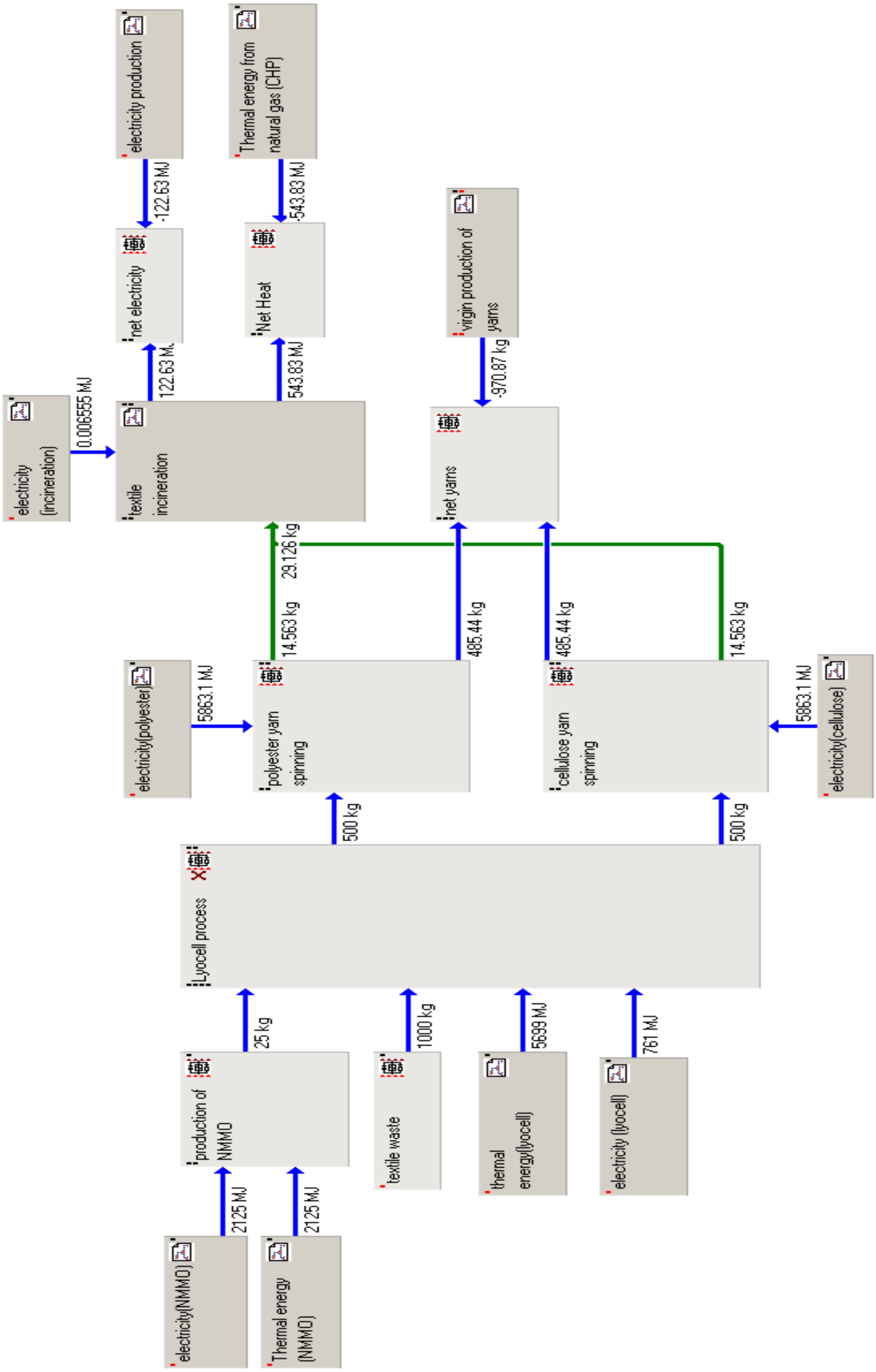
http://scholar.oxy.edu/, (Accessed August 2011)

Appendix A: GaBi models

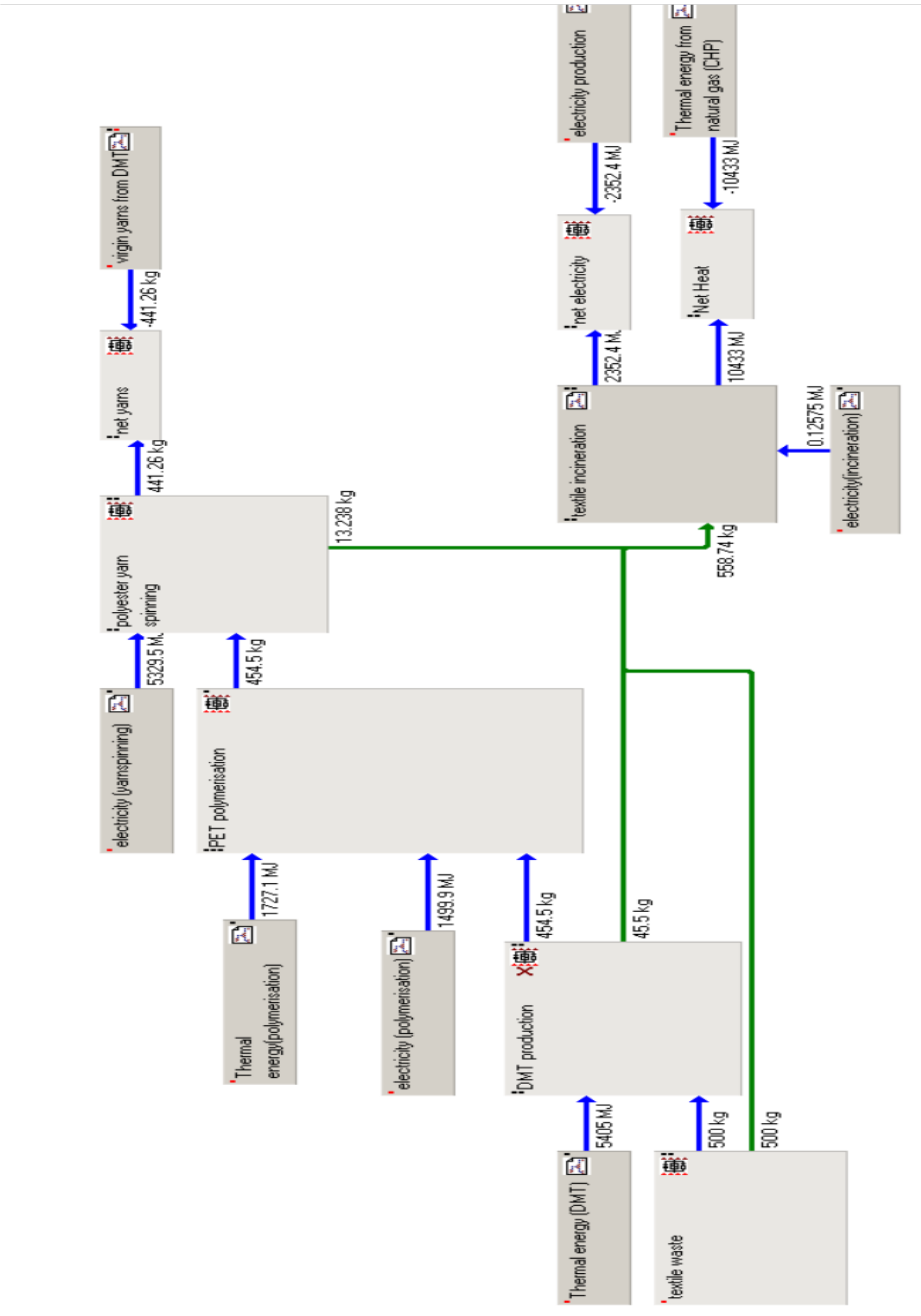
A1: Remanufacturing process



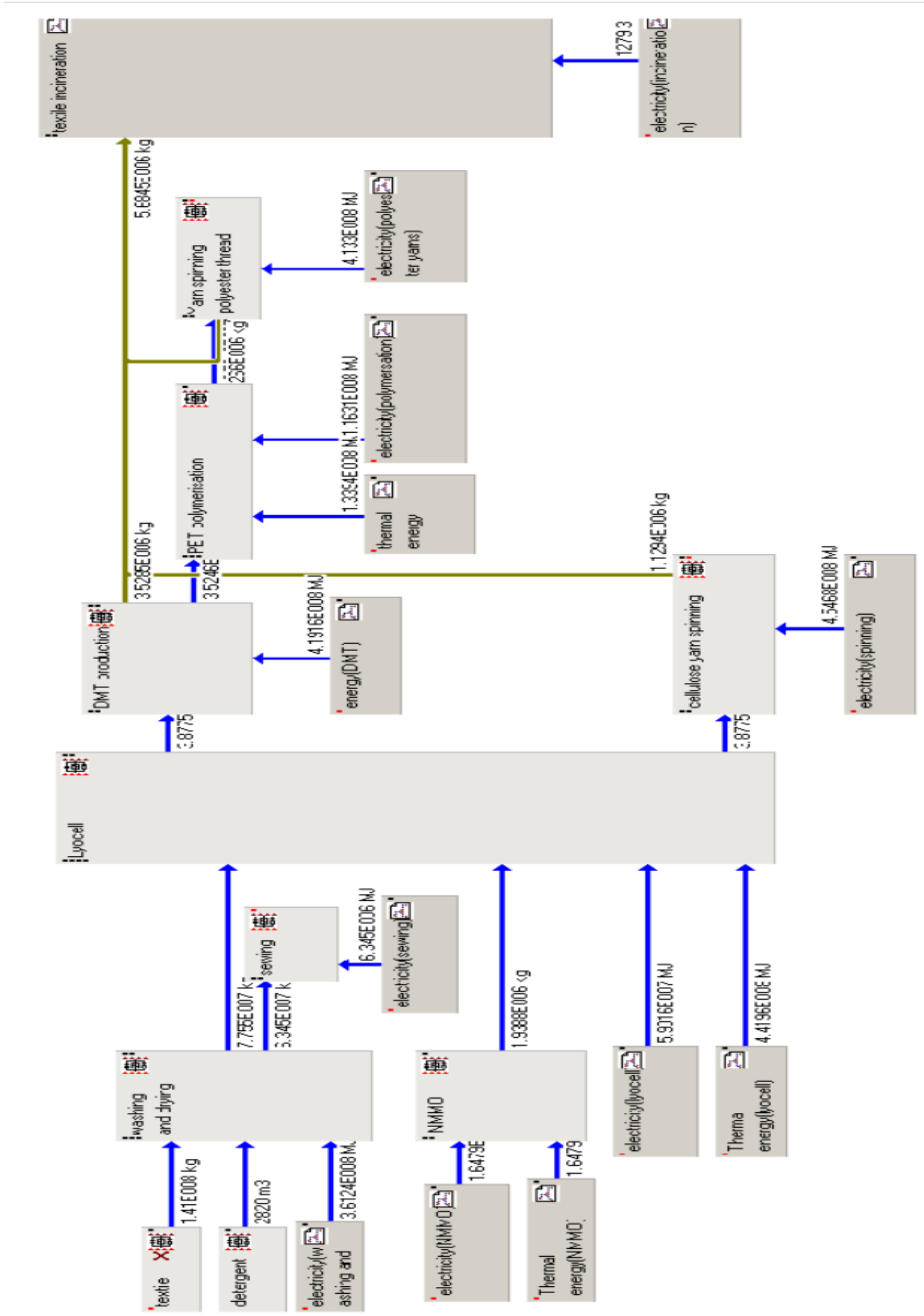
A2: Lyocell process



A3: Patagonia Process



A4: Integration of Scenarios



Appendix B: Inventory data

Remanufacturing process: washing, drying and sewing steps

Washing and drying step: according to Sumsung and Indosit washing machines, the amount of energy usage in the washing step per cycle equals to 1.02 kWh. According to Shinsemer et al (2004) [30] the average amount of electricity used by a drying machine equals to 3.25 kWh per cycle. I have assumed 6 kg of textile waste is washed and dried during each cycle. As the remanufacturing process has only been applied in small scale so far in Britain.

The total electrical energy consumption for washing and drying equals to 4.27 kWh/cycle (15.372 MJ/cycle). As the amount of textiles that would be washed and dried each time would be 6kg, the energy demand for 1000kg of textile equals to 2562 MJ of electricity.

The amount of detergent used in each cycle is 120 ml and consequently would be 0.02 cubic meters for 1 tonnes of textile [14].

Sewing step: I have assumed the product of the remanufacturing process is a textile wallet that weighs approximately 36 g. Based on ABS Alaskan power consumption of electrical appliances, the average required electricity for the sewing machine equals to 100 W. I have assumed that the time duration of sewing a textile wallet is 6 minutes, consequently the amount of electrical energy for sewing one textile wallet is 10 Wh (0.036 MJ).

Appendix C: Choosing higher and lower extremes in sensitivity analysis

C1: Lyocell process

The uncertainties that are determined through the sensitivity analysis are:

- The amount of required thermal energy for the Lyocell step: changing in the range of (-/+) 50%
- The source of thermal energy: changing from natural gas to Swedish district heating

The aim is to find out the potential range of the environmental performance of the system from energy usage and global warming potential perspective. In Figure C1, the results represent total global warming potential in 4 different cases, disregarding the system expansion as the changes have only been applied to the steps in the Lyocell process.

By combining two environmentally beneficial options, applying district heating as the source of thermal energy plus 50% reduction of thermal energy demand in the Lyocell step, the results for global warming potential are improved. See third bar in Figure C1.

On the other hand, the worst environmental performance is applied by combination of using natural gas as the source of thermal energy in addition to increasing the required thermal energy in the Lyocell step by 50%, See first bar in Figure C1.

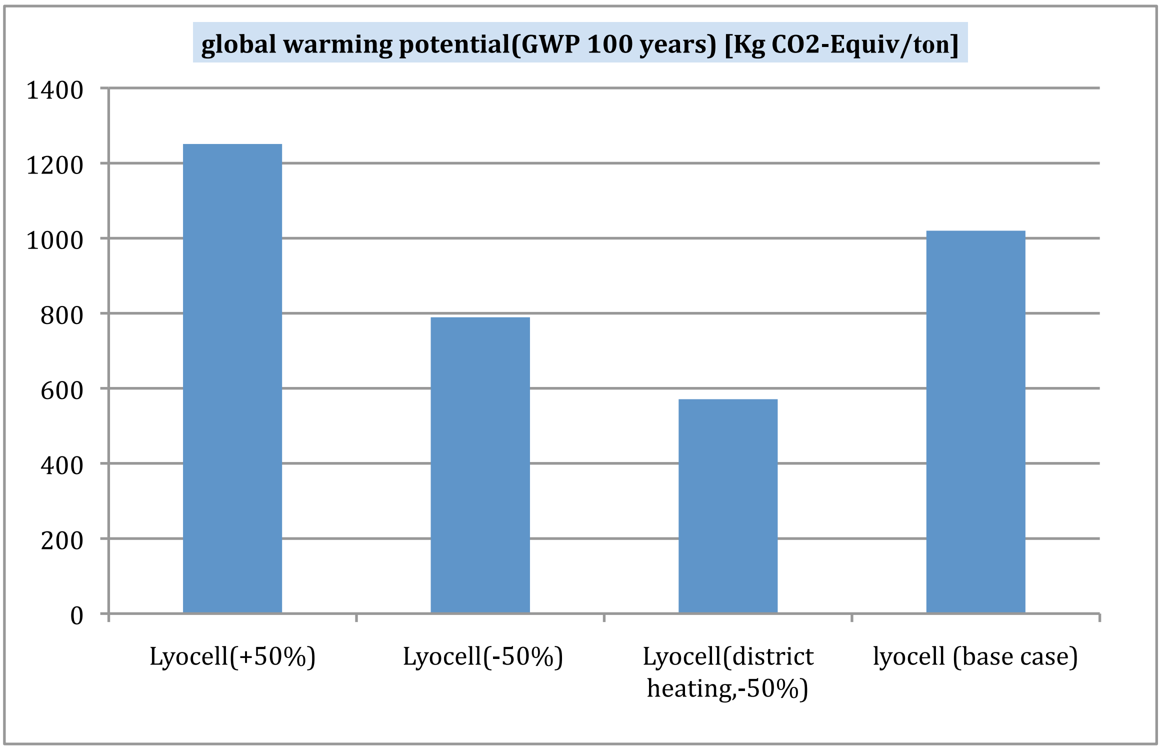


Figure C1 : Global warming potential of the foreground Lyocell process using different scenarios for thermal energy consumption and thermal energy source

In Figure C2, the results represent total primary energy usage in 4 different cases, disregarding the system expansion. By combining the two beneficial options of applying natural gas as the source of thermal energy plus 50% reduction of thermal energy demand in the Lyocell step, results for the primary energy usage are decreased, See first bar in Figure C2.

On the other hand, using district heating as the source of thermal energy in addition to increasing the required thermal energy in the Lyocell step by 50% will increase the total primary energy demand in the Lyocell process, See third bar in Figure C2.

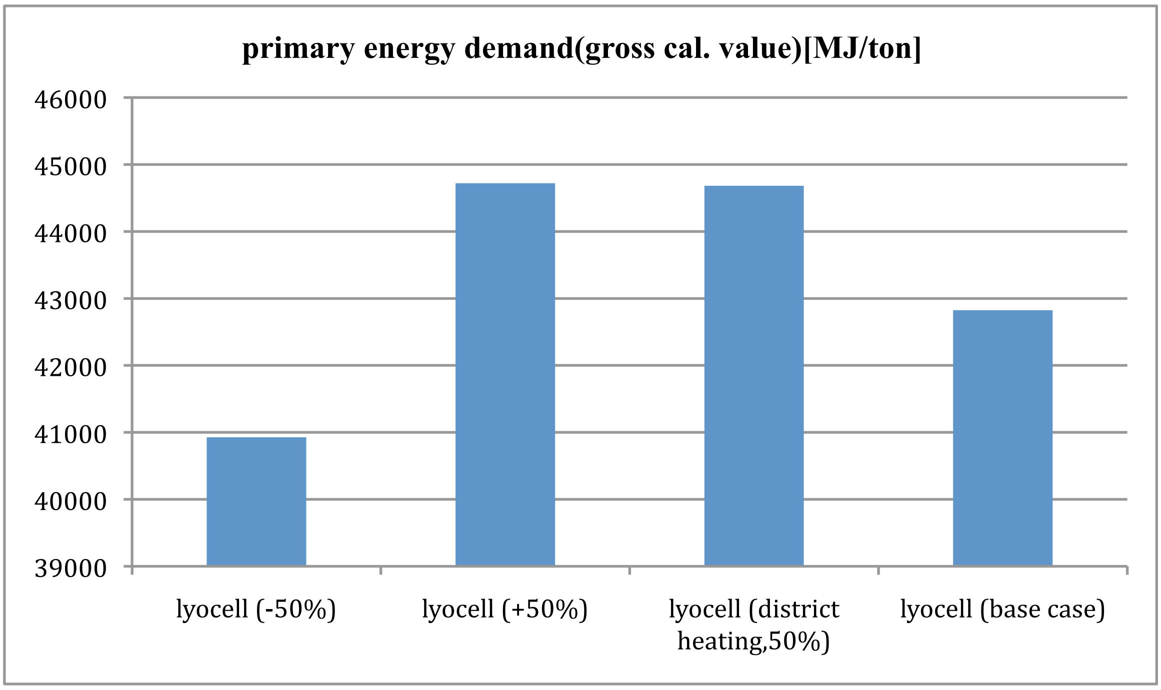


Figure C2: Primary energy demand for the foreground Lyocell process using different scenarios for thermal energy consumption and thermal energy source

C2 : Patagonia process

The uncertainties relating to the Patagonia process include:

- The amount of required thermal energy for the polymerization step. Changes have been applied in the range of (-/+) 50%
- The source of thermal energy: changing from natural gas to Swedish district heating

Changes were applied in order to find out the worst and the best-case scenario in environmental performance of the Patagonia technique. The aim is to find out the potential range of the environmental performance of the system from energy usage and global warming potential perspective.

In Figure C3, the results represent total global warming potential in 4 different cases,disregarding the system expansion as the changes have only been applied to the steps of the Patagonia process. By combining two environmentally beneficial options, applying district heating as the source of thermal energy plus 50% reduction of thermal energy demand in the polymerization step, the results for global warming potential are improved. See third bar in Figure C3.

On the other hand, the worst environmental performance is applied by combination of using natural gas as the source of thermal energy in addition to increasing the required thermal energy in polymerization step by 50%, See first bar in Figure C3.

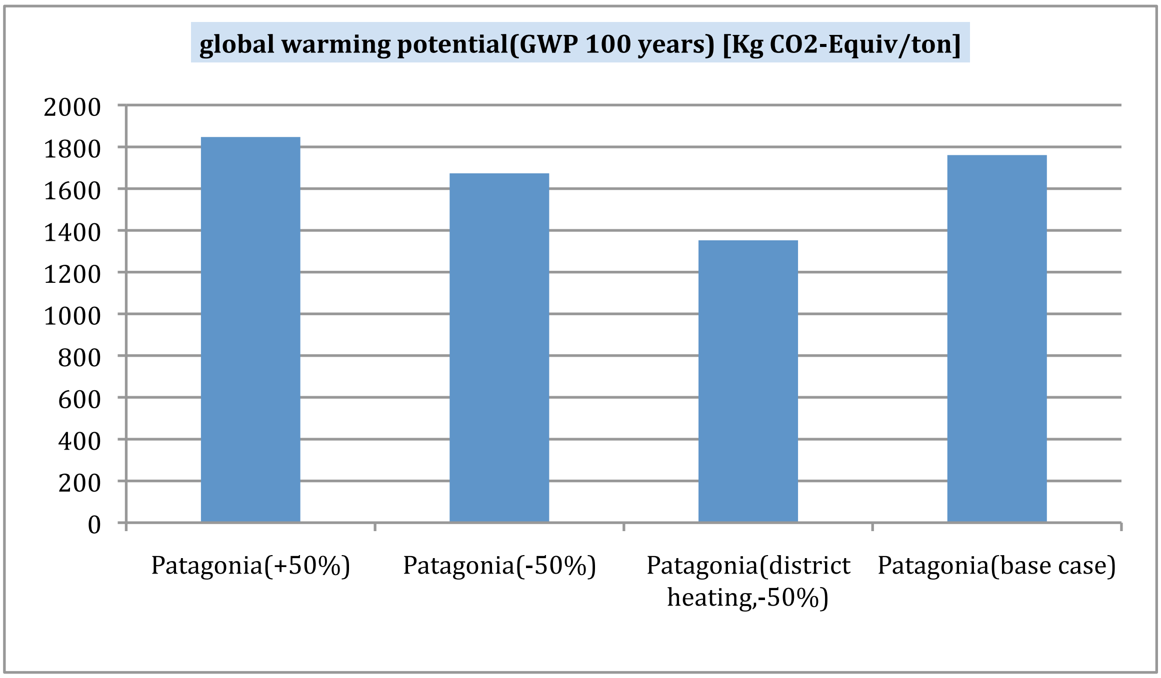


Figure C3: Global warming potential in foreground Patagonia process using different scenarios for thermal energy consumption and thermal energy source

In Figure C4, the results represent total primary energy usage in 4 different cases, disregarding the system expansion. By combining the two beneficial options of applying natural gas as the source of thermal energy plus 50% reduction of thermal energy demand in the polymerization step, results for the primary energy demand are decreased, See first bar in Figure C4.

On the other hand, using district heating as the source of thermal energy in addition to increasing the required thermal energy in the polymerization step by 50% will increase the total primary energy demand in the polymerization step, See third bar in Figure C4.

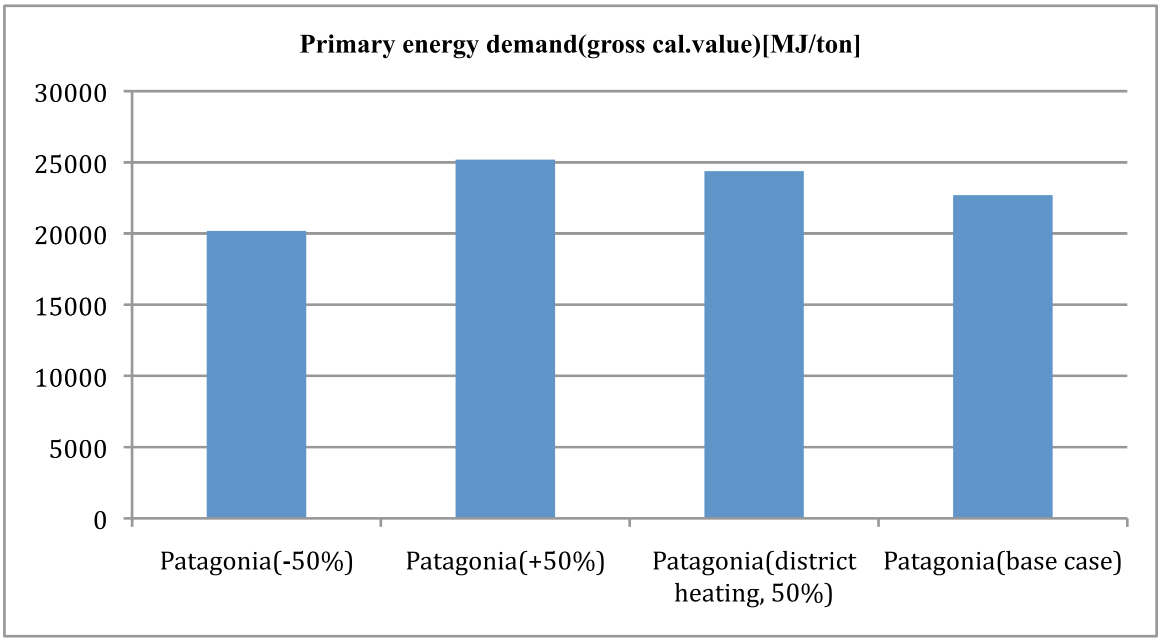


Figure C4: Primary energy demand for the foreground Patagonia process using different scenarios for thermal energy consumption and thermal energy source

Appendix D: Virgin production of textile wallet

Since the result of the remanufacturing process is directly depandant to virgin production process of textile wallet, more analysis for finding out the most contributors in the results has been applied.

Results regard to the global warming potential and primary energy usage of the virgin production process of textile wallet are presented.

As shown in Figure D1, enviromental sysem performance of the process has been investigated from the global warming potential aspect. Results are shown in kg CO_2-Equivalent emissions per kg of textile wallet.

As can be seen the most significant contribution in global warming potential is related to the usage of electrical energy that is provided by average Chinese electricity mix.

Moreover the process of producting cellulose and polyester fibers from virgin materials has a considerable role on the resutls relating to global warming potential.

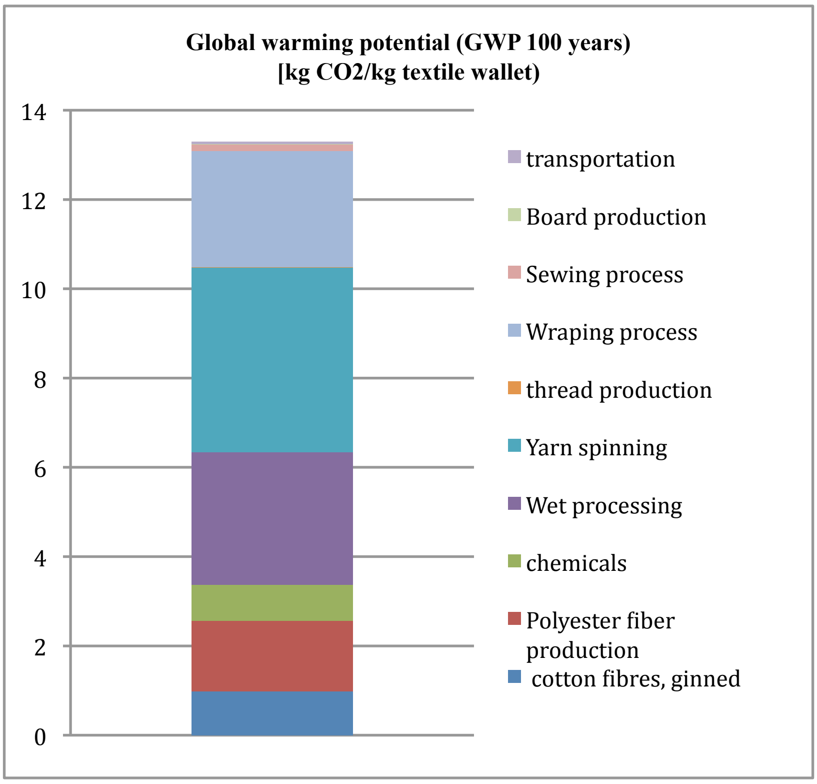


Figure D1. Global warming potential of steps in virgin production process of textile wallet

Figure D2, presents the result of primary energy demand in the steps of virgin production process of textile wallet. Results are shown in gross calorific value in MJ/ kg of produced textile wallet.

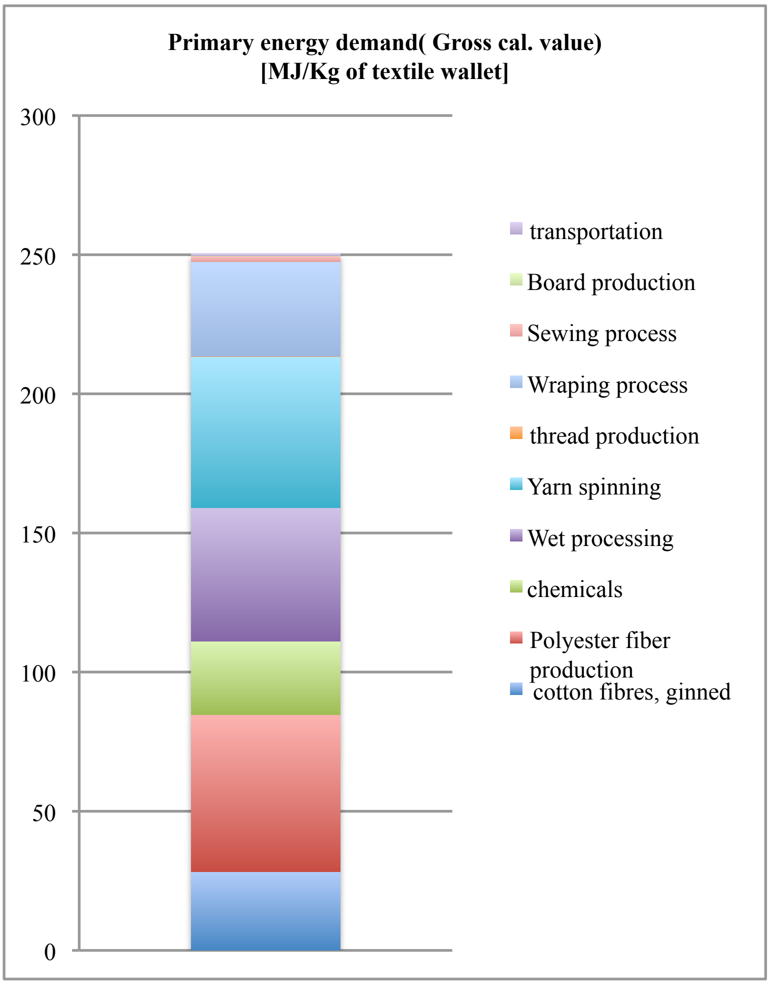


Figure D2. Primary energy usage of steps in virgin production process of textile wallet

As can be seen production of polyester and cellulose fibers from virgin materials reqired considerable amount of energy. The required amount of electrical energy due to yarn spinning, wet processing and wraping process is the significant contributors to results of primary energy demand.

Appendix E: Results of the cases

E1.Incineration

Table E1. global warming potential in each steps of Incineration (kg CO_2-Equiv/ tonne of textile waste)

Process	Global warming potential (CML 2007)
Textile incineration	1840
Alternative for thermal energy production	-1500
Alternative for electricity production	-95

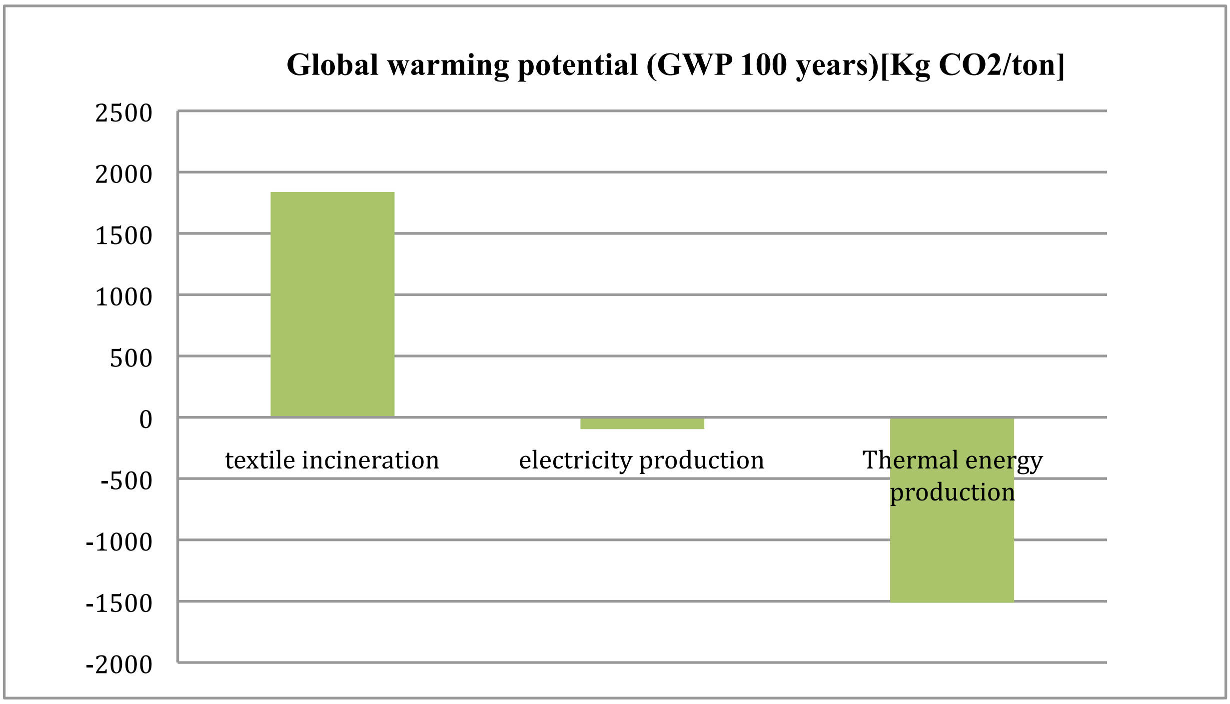


Figure E1. Global warming potential in each steps of Incineration process

Table E2. Primary energy usage in each steps Incineration (MJ/ tonne of textile waste)

Process	Primary energy demand
Textile incineration	660
Alternative for thermal energy production	-10800
Alternative for electricity production	-12400

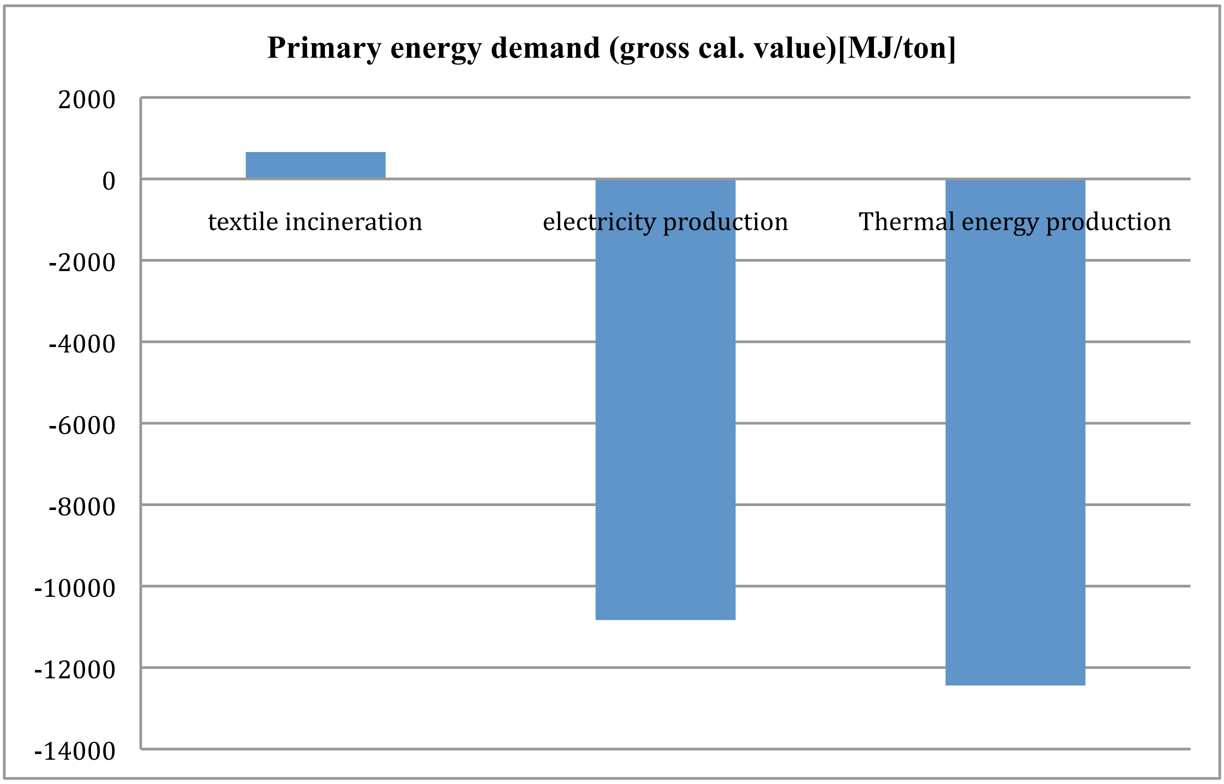


Figure E2. Primary energy demand in each step of Incineration process

E2.Remanufacturing process

Table E3. global warming potential in each steps of Remanufacturing (kg CO_2-Equiv/ tonne of textile waste)

Process	**Global warming potential (CML 2007)**
Detergent production	40
Washing and Drying	60
Sewing	1
Residue incineration	1010
Virgin textile wallet production	-6090
Alternative for thermal energy production	-830
Alternative for electricity production	-50

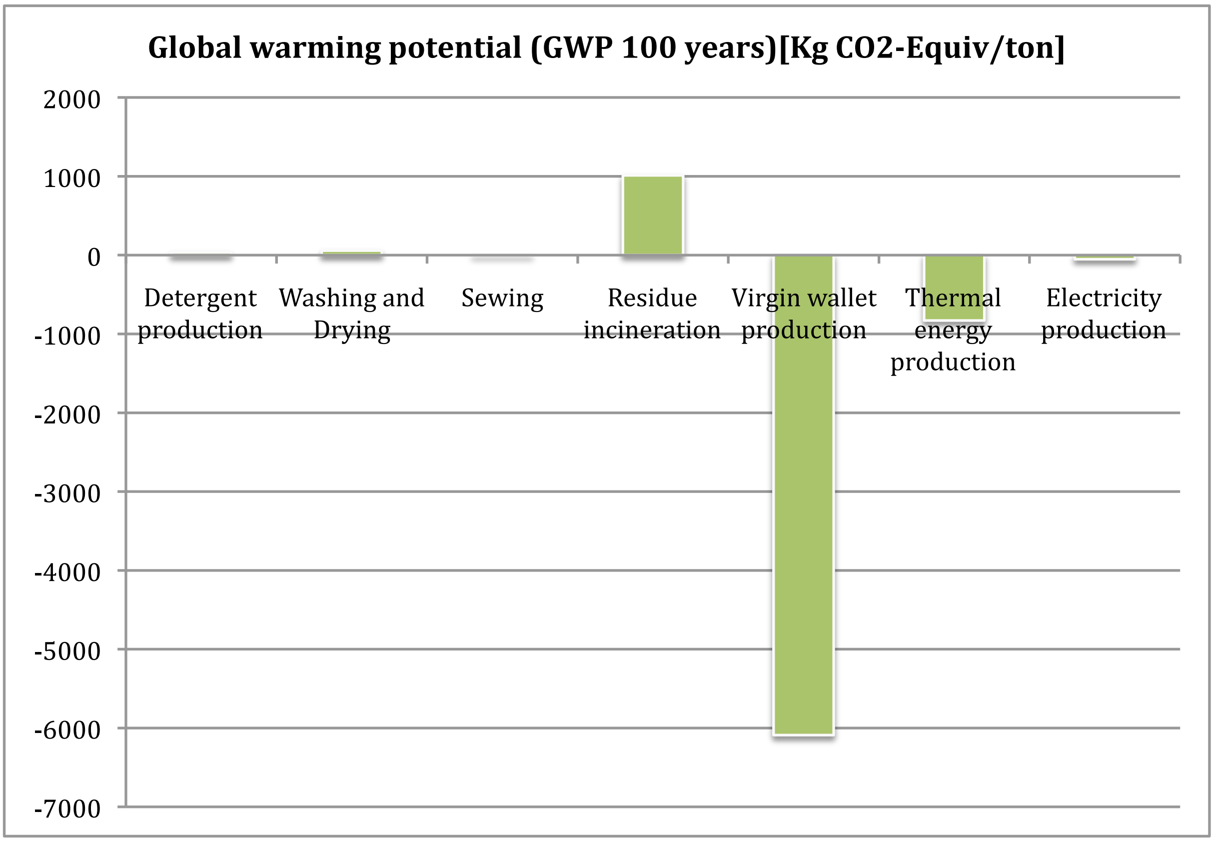


Figure E3. Global warming potential in each steps of Remanufacturing process

Table E4. Primary energy usage in each steps of Remanufacturing (MJ/ tonne of textile waste)

Process	**Primary energy demand**
Detergent production	- (missing data)
Washing and Drying	6600
Sewing	110
Residue incineration	360
Virgin textile wallet production	-114000
Alternative for thermal energy production	-6800
Alternative for electricity production	-6000

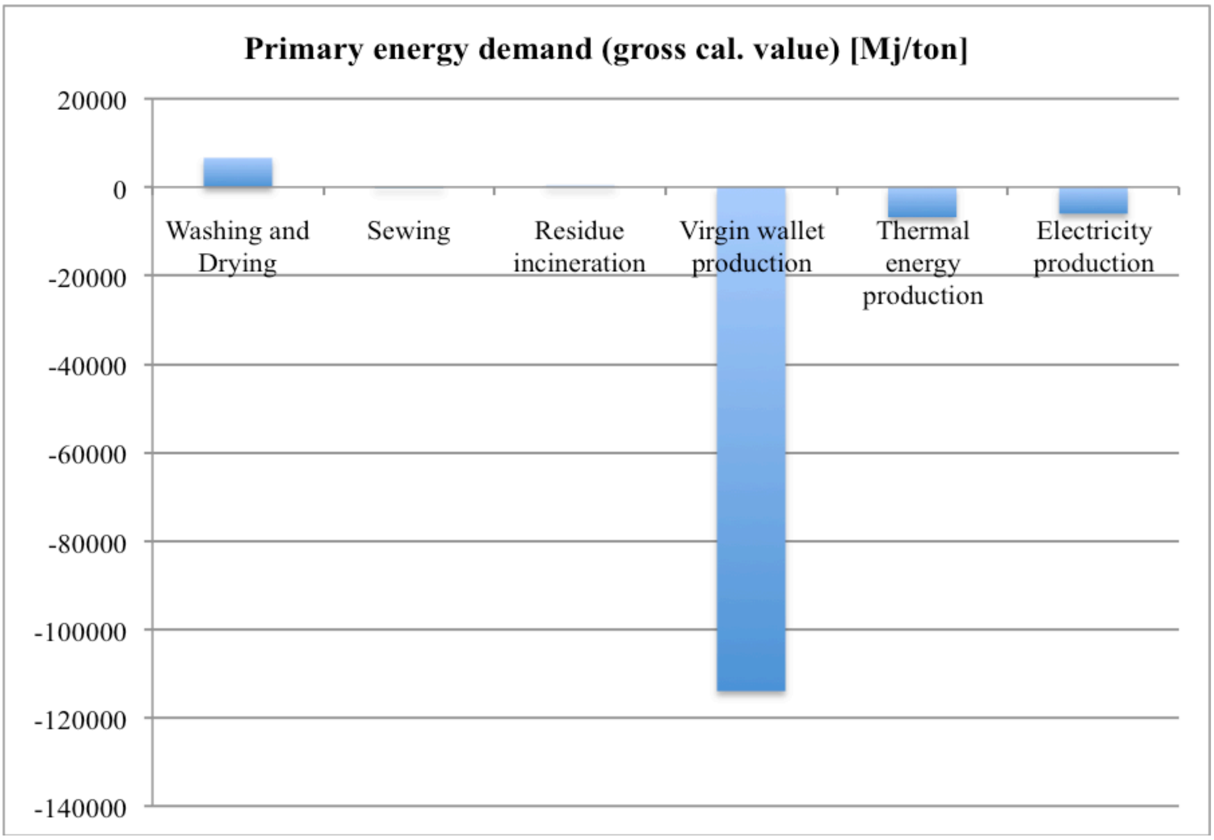


Figure E4. Primary energy demand in each step of Remanufacturing process

E2.Lyocell process

Table E5. global warming potential in each steps of Lyocell (kg CO_2-Equiv/ tonne of textile waste)

Process	**Global warming potential (CML 2007)**
NMMO production (thermal energy)	170
NMMO production (electricity)	50
Lyocell step (thermal energy)	460
Lyocell step (electricity)	20
Yarn spinning (Cellulose)	130
Yarn spinning (Polyester)	130
Residue incineration	50
Virgin production of yarns	-6530
Alternative thermal energy	-45
Alternative electricity production	-3

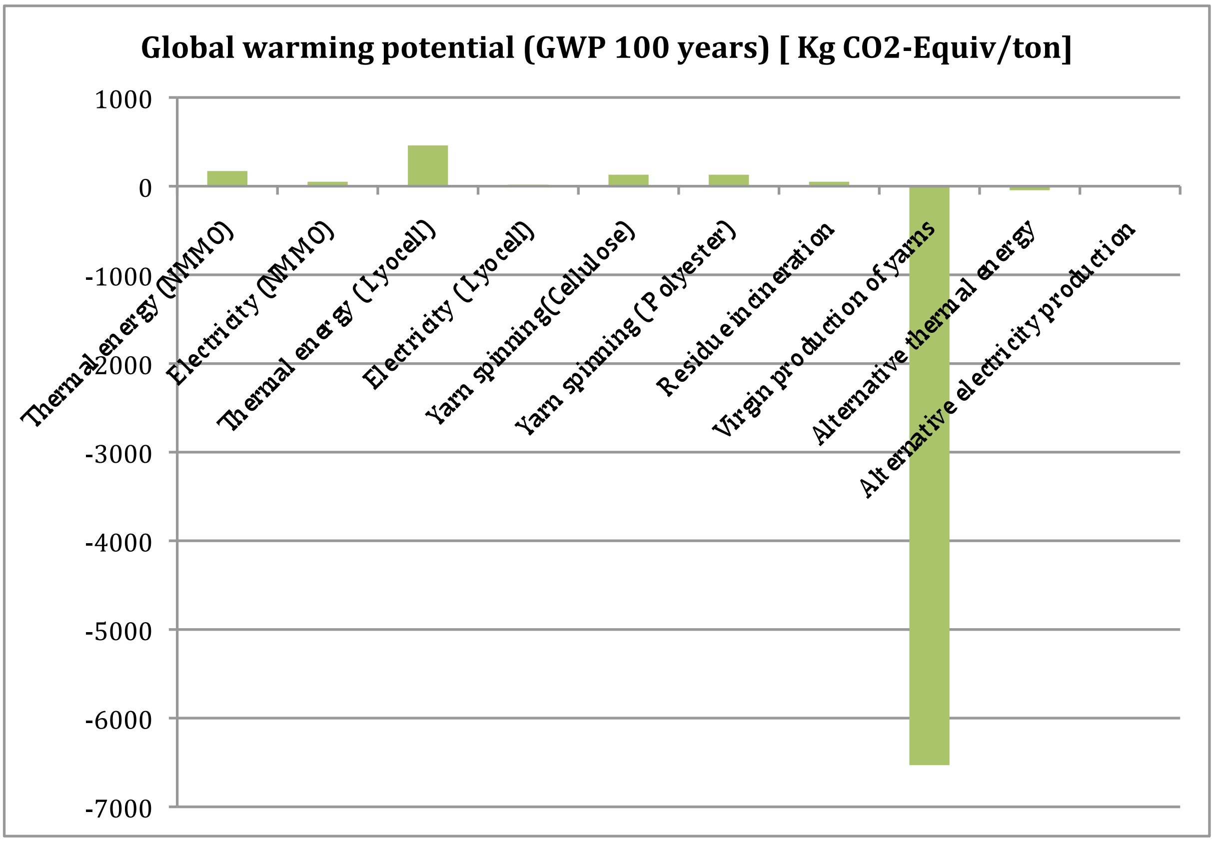


Figure E5. Global warming potential in each steps of Lyocell

Table E6. Primary energy usage in each steps of Lyocell (MJ/ tonne of textile waste)

Process	**Primary energy demand**
NMMO production (thermal energy)	1400
NMMO production (electricity)	5400
Lyocell step (thermal energy)	3800
Lyocell step (electricity)	1900
Yarn spinning (Cellulose)	15000
Yarn spinning (Polyester)	15000
Residue incineration	20
Virgin production of yarns	-133000
Alternative thermal energy	-360
Alternative electricity production	-310

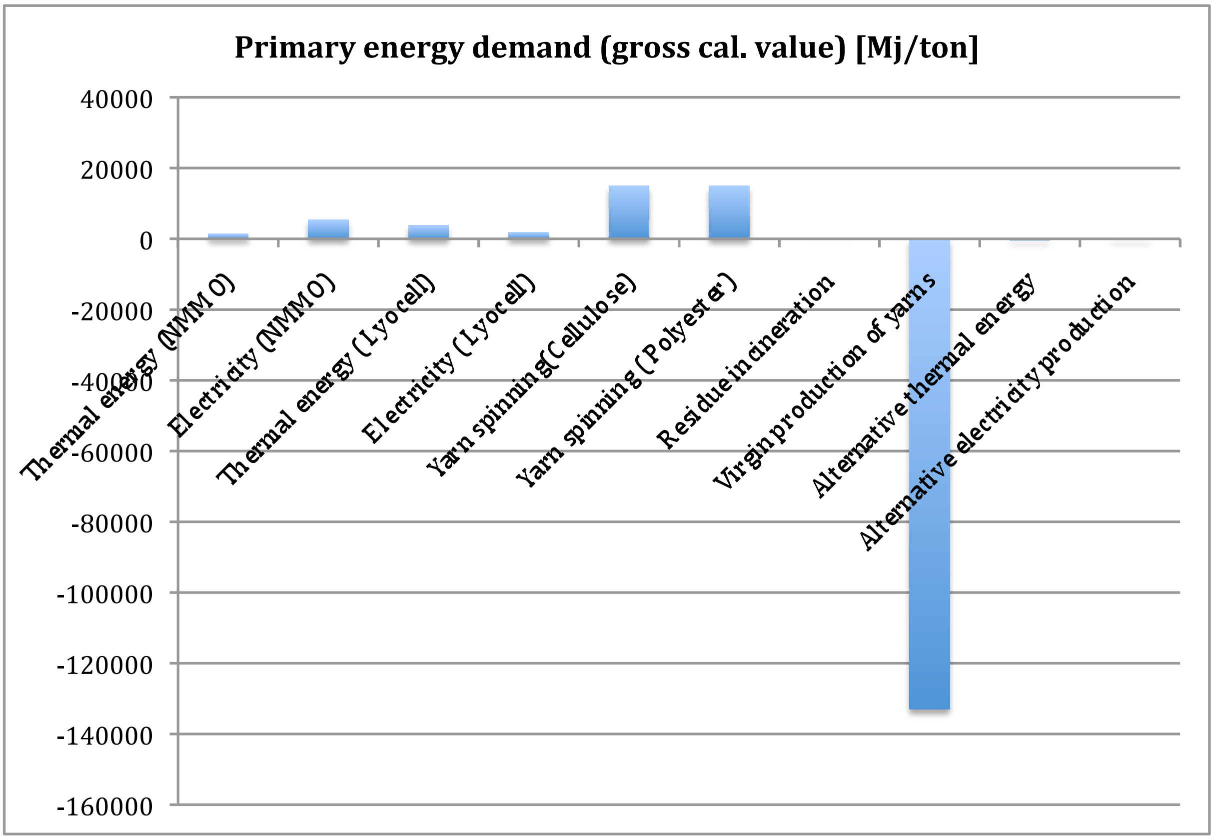


figure E6. Primary energy demand in each steps of Lyocell

E3.Patagonia

Table E7. global warming potential in each steps of Patagonia (kg CO_2-Equiv/ tonne of textile waste)

Process	**Global warming potential (CML 2007)**
Production of DMT	440
Polymerization (thermal energy)	140
Polymerization (electricity)	35
Yarn spinning	120
Residue incineration	1030
Virgin yarns from DMT	-2940
Alternative thermal energy	-845
Alternative electricity production	-50

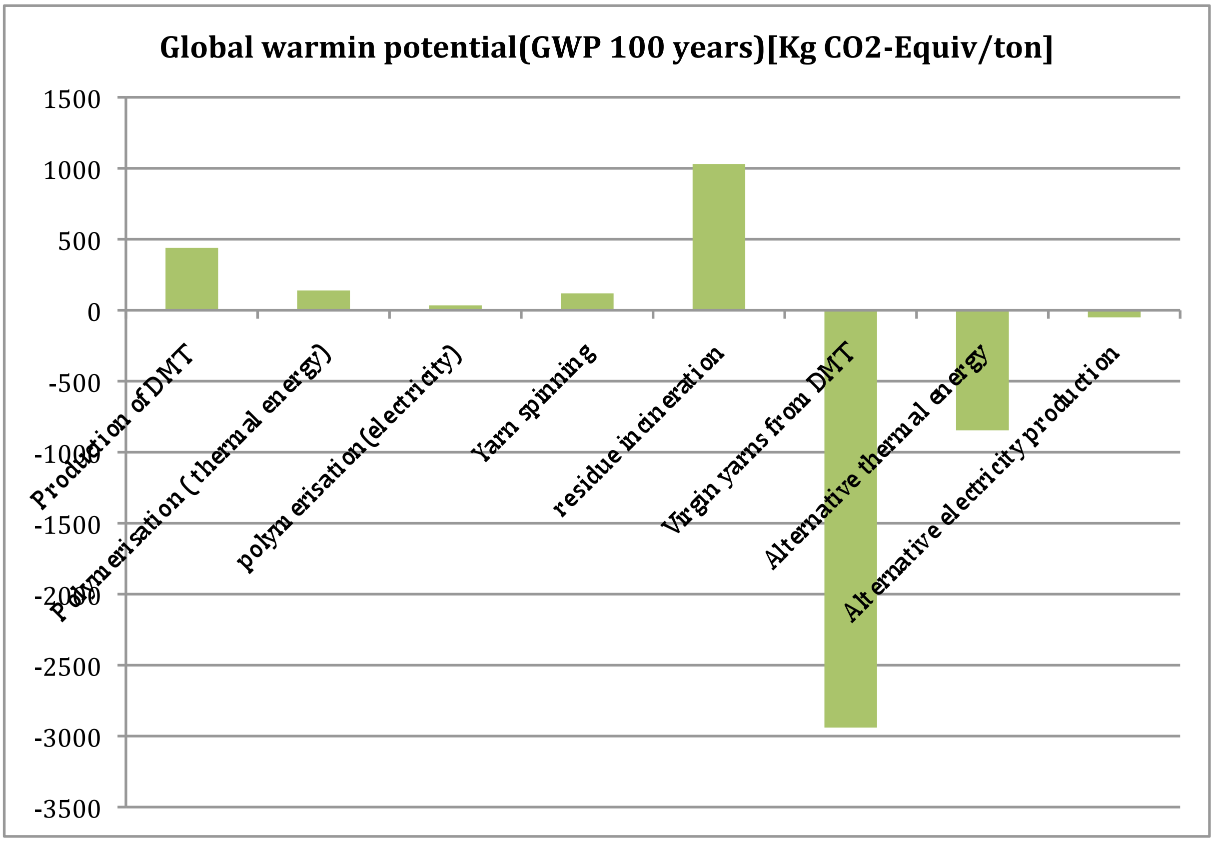


Figure E7: Global warming potential in each steps of Patagonia process

Table E8. Primary energy usage in each steps of Patagonia (MJ/ tonne of textile waste)

Process	**Primary energy demand**
Production of DMT	3600
Polymerization (thermal energy)	1200
Polymerization (electricity)	3800
Yarn spinning	13700
Residue incineration	400
Virgin yarns from DMT	-40500
Alternative thermal energy	-7000

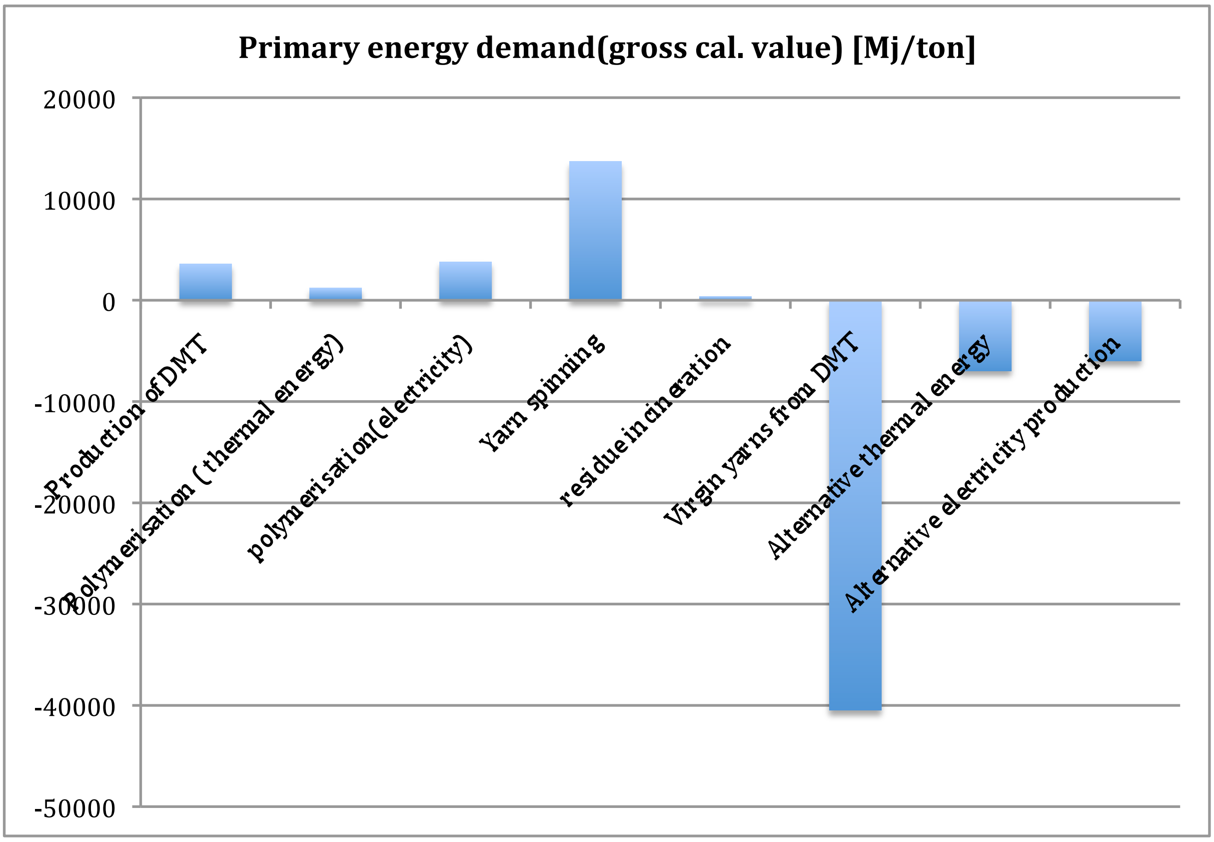


Figure E8. Primary energy demand in each steps of Patagonia process