LIFE CYCLE ASSESSMENT OF EVAPORATIVE RECOVERY OF MERCERIZATION WASTEWATER

A THESIS SUBMITTED TO
THE GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES
OF
MIDDLE EAST TECHNICAL UNIVERSITY

BY

EDA BAYAR

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR
THE DEGREE OF MASTER OF SCIENCE
IN
ENVIRONMENTAL ENGINEERING

DECEMBER 2015

Approval of the thesis:

LIFE CYCLE ASSESSMENT OF EVAPORATIVE RECOVERY OF MERCERIZATION WASTEWATER

submitted by **EDA BAYAR** in partial fulfillment of the requirements for the degree of **Master of Science in Environmental Engineering Department, Middle East Technical University** by,

Prof. Dr. Gülbin Dural Ünver _______________________
Dean, Graduate School of **Natural and Applied Sciences**

Prof. Dr. Kahraman Ünlü _______________________
Head of Department, **Environmental Engineering**

Prof. Dr. Ülkü Yetiş _______________________
Supervisor, **Environmental Engineering Dept., METU**

Examining Committee Members:

Prof. Dr. Filiz Bengü Dilek _______________________
Environmental Engineering Dept., METU

Prof. Dr. Ülkü Yetiş _______________________
Environmental Engineering Dept., METU

Assoc. Prof. Dr. Emre Alp _______________________
Environmental Engineering Dept., METU

Assoc. Prof. Dr. Gökşen Çapar _______________________
Water Management Institute, Ankara University

Assist. Prof. Dr. Çağla Meral _______________________
Civil Engineering Dept., METU

Date: 11.12.2015

I hereby declare that all information in this document has been obtained and presented in accordance with academic rules and ethical conduct. I also declare that, as required by these rules and conduct, I have fully cited and referenced all material and results that are not original to this work.

Name, Last name: Eda Bayar

Signature:

ABSTRACT

LIFE CYCLE ASSESSMENT OF EVAPORATIVE RECOVERY OF MERCERIZATION WASTEWATER

Bayar, Eda

M. S., Department of Environmental Engineering

Supervisor: Prof. Dr. Ülkü Yetiş

December 2015, 131 pages

The products of textile industry are irrevocable part of our lives: clothes, carpets, towels etc. However, textile industry is known to be having impact on the environment, especially for its high levels of water consumption and waste generation.

The European Union's Industrial Emissions Directive (former IPPC Directive) requires industrial establishments to apply best available techniques (BAT) both in the production processes and in the waste treatment and disposal. The European IPPC Bureau (EIPPCB) produces sectorial best available techniques reference documents (BREFs) to co-ordinate the exchange of information between Member States concerned on BAT. The BREF prepared for textile industry recommends the application of hundreds of different techniques in the manufacture of textiles and also in the management of textile effluents. Recovery of highly alkaline wastewater formed during mercerization process by the technique of evaporation is among the BAT suggested for the textile industry. In the context of this study, three scenarios are established based on fuels used for steam production which is used in evaporative recovery (heavy fuel oil, light fuel oil and natural gas). Evaporation process is evaluated in terms of its impacts on the environment by using a life cycle assessment (LCA) tool and the environmental burdens of this process is compared to those of conventional end-of-pipe treatment option.

By the aid of the SimaPro software, three scenarios of evaporation and the base-line scenario of end-of-pipe treatment (neutralization and activated sludge process) is evaluated selecting- one kg of mercerization wastewater as functional unit and setting boundary conditions as “cradle to grave”. The well-known IMPACT2002+ method is used for environmental impact analysis.

The processing of 1 kg of alkaline weak lye from mercerization process by evaporation (which is using natural gas for steam production) is found to be the most environmentally friendly for the recovery of caustic caused the following major environmental impact potentials: global warming potential of 9.89E-05 kg CO2 eq; respiratory inorganics release of 7.44E-05 kg $PM_{2.5}$ into air_{-eq}; and non-renewable energy use of 0.000127 MJ. However, application of evaporative recovery was not found to improve the environmental performance of mercerization process for all impact categories in comparison with the baseline scenario of end-op-pipe treatment. In particular, impacts due to non-renewable energy and global warming potential were found to be increased to the largest extent with 1.2% and 1.24%, respectively.

An economical comparison of evaporative recovery and end-of-pipe treatment of weak lye was also carried out and profitability was analyzed to assess the evaporative recovery option’s potential return on investment using Net Present Value (NPV) analysis. The results indicated that the application of evaporative recovery of weak lye is profitable and therefore it complies with economical standards.

Keywords: Life Cycle Assessment, Mercerization Wastewater, Textile Industry, Evaporation, Weak Lye

ÖZ

KOSTİK MERSERİZASYON ATIK SUYUNUN BUHARLAŞTIRMA YÖNTEMİ İLE GERİ KAZANIMININ YAŞAM DÖNGÜSÜ ANALİZİ

Bayar, Eda
Yüksek Lisans, Çevre Mühendisliği Bölümü
Tez Yöneticisi: Prof. Dr. Ülkü Yetiş
Aralık 2015, 131 sayfa

Tekstil endüstrisinin ürünleri günlük yaşamımızın olmazsa olmazıdır: kıyafetler, halılar, havlular vb. Fakat tekstil endüstrisi çevre üzerindeki etkisiyle, özellikle yüksek seviyede su tüketimiyle ve atık üretimi ile bilinmektedir.

BREF (Mevcut en iyi teknikler- referans doküman),Avrupa Birliği'nin Endüstriyel Emisyonlar Direktifi (Eski IPPC Direktifi) kapsamında oluşturulmuş olup, hem üretim hem de atık arıtımı ve bertarafı konularında endüstriyel kuruluşların Mevcut En Iyi Tekniklerini (MET) uygulamalarını sağlar. Avrupa Entegre Kirlilik Önleme ve Kontrolü Bürosu sektörel Mevcut En İyi Teknikler- referans dokümanlarını çıkararak üye ülkeler arasında bilgi alış-verişini koordine etmektedir. Söz konusu doküman, tekstil konusunda yüzlerce tekniği ve tekstil atıklarının yönetimi konularını içerecek şekilde tekstil endüstrisi için de düzenlenmiştir. Bu tez çalışması çerçevesinde, evaporasyonda kullanılan buharın üretimi için kullanılan yakıtlar baz alınarak üç farklı senaryo oluşturulmuştur. (ağır akaryakıt, hafif akaryakıt ve doğalgaz) Evaporasyon prosesi, çevre üzerindeki etkileri açısından Yaşam Döngüsü Analizi (YDA) ile değerlendirilmiş ve çevresel yük oluşturan bir arıtma türü olan boru-çıkışı-arıtma ile evaporasyon prosesi karşılaştırılmıştır.

SimaPro yazılımının yardımıyla, evaporasyon için oluşturulan üç senaryo ve eskiden kullanımda olan boru-çıkışı-arıtma yönteminin (nötralizasyon ve aktif çamur) çevresel etkilerini belirlemek için aracılığıyla 1 kg merserizasyon atık suyu birim ünite olarak; sistem sınırları "beşikten mezara" olarak seçilip, karşılaştırılacaktır. İyi bilinen IMPACT 2002+ metodu çevre etki analizlerinde kullanılmaktadır.

1 kg'lık alkali zayıf çözeltinin evaporasyon ile geri kazanımı için oluşturulan senaryolar arasından buhar üretimi için doğalgaz kullanılan senaryo en çevre dostu senaryo bulunmuştur. Potansiyel çevresel etkileri inorganiklerin solunuma etkileri - 7.44E-05kg $PM_{2.5}$; küresel ısınma 9.89E-05kg CO_2, yenilenemeyen enerji 0.000127 MJ olarak bulunmuştur. Fakat, bahsi geçen evaporasyon senaryosunun referans senaryo olan eski arıtma metodu ile kıyaslandığında çevresel performansı artırmadığı gözlenmiştir. Özellikle yenilenemeyen enerji ve küresel ısınma en yüksek düşüşü göstererek sırasıyla %1.2 ve %1.24 oranında artmıştır.

Evaporasyon ve referans senaryo olan boru-çıkışı-arıtmanın ekonomik bir analizi de Net Bugünkü Değer yöntemi ile yapılmıştır ve evaporasyonun karlılığı analiz edilerek yatıım maliyetini geri kazandırma potansiyeli değerlendirilmiştir. . Evaporasyon yönteminin karlılık sağladığı için daha iyi bir yöntem olduğu belirlenmiştir. Merserizasyon atık suyunun evaporasyonu üreticilerin su, kimyasal ve ısı tasarrufu yapmalarını sağlar. Elde edilen sonuçlara göre, evaporasyon ekonomik standartlara uymaktadır.

Anahtar Kelimeler: Yaşam Döngüsü Analizi, Merserizasyon Atık suyu, Tekstil Endüstrisi, Evaporation

To my family

ACKNOWLEDGMENTS

I would like to express my deepest gratefulness to my distinguished supervisor, Prof. Dr. Ülkü Yetiş, who had been guiding me with her valuable knowledge and strong patience, during thesis-writing process. Her ideas, unique insight and guidance have helped me gain a perspective, which cannot be learned from any textbook.

I also would like to share my deepest feelings with my dearest friends Şeyma Karaçay Lokmacı and Burak Çakırlar; and my colleagues Bahar Özöğüt and Erol Çavuş who helped me a lot during this process with their knowledge and moral support.

Another person whom I would like to share my gratitude with, Mustafa İnalöz, without his support I definitely could not end this thesis work. Turkey needs engineers who love their country and don't hesitate to contribute to scientific studies of its people.

And last but not least, I am blessed with having such a family who loves supports and believes in me. Especially, my father, who has been guiding me with his life experiences, pushing my limits sometimes but never stops believing in me; I will never disappoint you. I appreciate everything you provided for me.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

ABBREVIATIONS

AOX	Adsorbable organic halides
BAT	Best Available Techniques
BATAEL	BAT associated emission limit values
Bé°	Baume
BOD	Biochemical oxygen demand
BREF	Best Available Techniques Reference Document
CF	Characterization factors
COD	Chemical oxygen demand
DALY	Disability adjusted life years
DQI	Data quality indicator
ELV	Emission limit value
EPA	Environmental protection agency
GDP	Gross domestic product
HFO	Heavy Fuel Oil
IED	Industrial Emissions Directice
IMPACT2002+	IMPact Analysis of Chemical Toxics
IPPC	Integrated Pollution Prevention and Control
ISO	International organization for standardization
LCA	Life Cycle Assessment
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
LFO	Light Fuel Oil
MJ	Mega Joules
NF	Nanofiltration
NG	Natural Gas
NPV	Net Present Value
PDF	Potentially Disappeared Fraction
RO	Reverse osmosis
TDS	Total dissolved solids

TDS	Total dissolved solids
TOC	Total organic carbon
TSS	Total suspended solids
UNCED	United Nations Conference on Environment and Development
VSS	Volatile suspended solids

CHAPTER 1

INTRODUCTION

The products of textile industry are essential parts our daily life they are used for home furnishing, clothing, and industrial use. According to a report of the Ministry of Science, Industry and Technology, Turkey has 3.5% share of world's textile and garments export. Textiles industry provides more than 10% of Turkey's GDP [1].

Textiles industry has a huge demand for water during several production phases and generates huge volume of wastewaters. Moreover, the manufacture of various textile products requires a great variety of processes employing a great variety of chemicals and dyes. At the end, wastewaters heavily loaded with chemicals/dyes and therefore usually requiring tertiary treatment are produced.

On the other side, implementation of pollution prevention measures can result in significant economic and environmental benefits with respect to wastewater management. Many governments aim to prevent the consumption and control pollution arising from activities of textile industry. Turkey has Integrated Pollution Prevention and Control Communique for Textile Industry[1], for regulation of measures to be taken to minimize environmental effects rising from textile industries' activities.

[1] Integrated Pollution Prevention and Control Communique for Textile Industry Communiqué, Official Gazette dated10.03.2015 Numbered 29291.

Industrial Emissions Directive (2010/75/EU) offers some techniques in order to achieve integrated management of sources via BREFs. These documents are used as a guideline, “aiming high level protection of the environment as a whole” [2]. The BREFs are produced specific to several sectors, one of which is textiles industry. The BREFs consider sub-sectors, sub-processes, materials, emission levels, techniques, emerging technologies.

Textiles production starts with production of yarn. Yarn can be of animal based (wool, silk), plant based (cotton, linen) and synthetic (nylon, acrylic). The production ends with finishing processes. The general flowchart for cotton textile processing is shown in Figure 1.

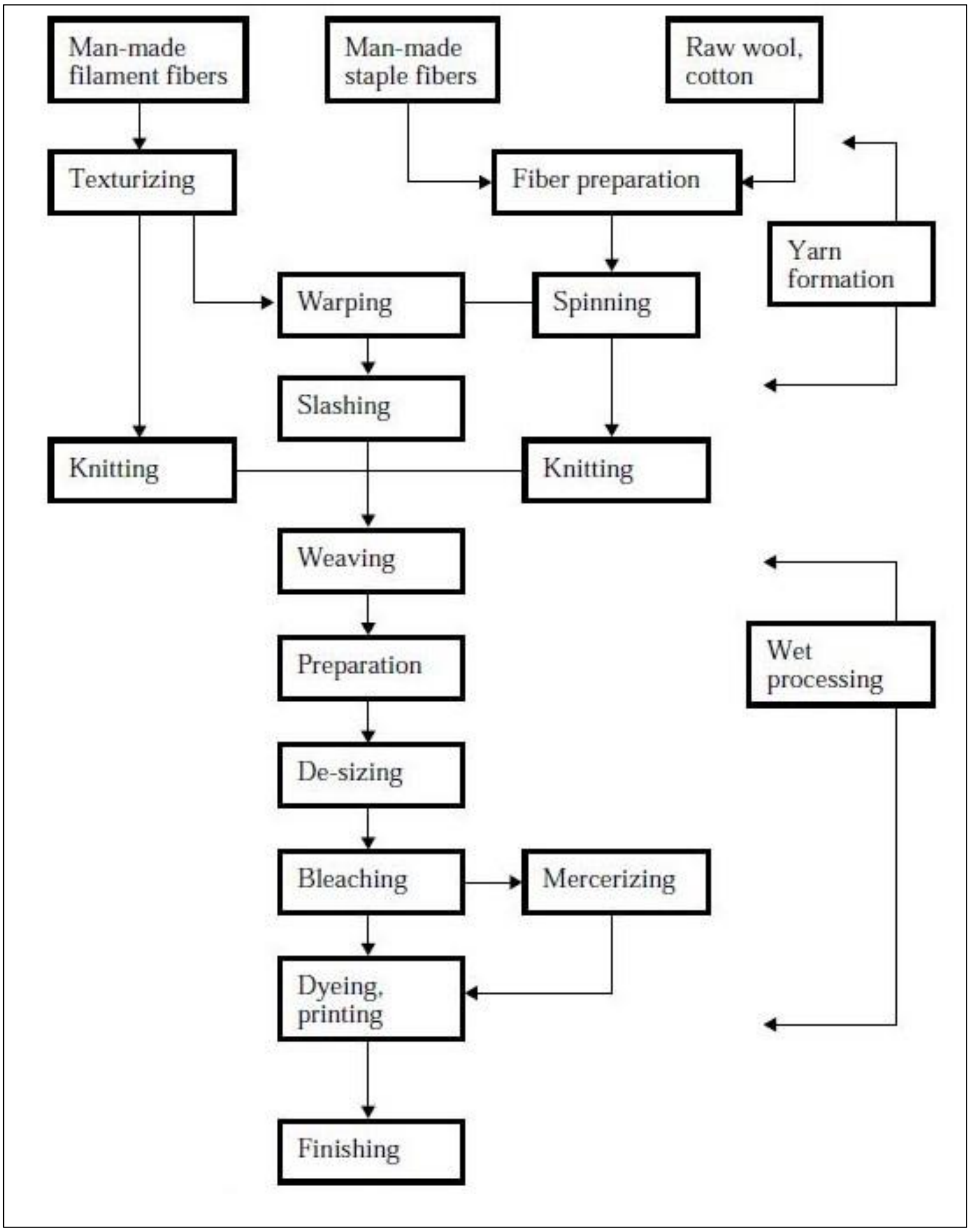

Figure 1. Processes for cotton processing textile mill [3]

Weaving, preparation, de-sizing, bleaching, dyeing, printing and finishing processes are called wet processing since vast amounts of water is used. After wet processing, wastewater with variety of chemicals is produced. Wet processing is done to obtain different types and values of fabric, serving demands of end-users. According to EPA [4], a textile factory's 70-85% of water use is due to processing while 15-20% is required by steam production. Some of the pollutants in the wastewater can be given as: BOD, COD, AOX, NaOH, surfactants, high pH, color, fats, oils, metals, suspended solids, salts, solvents etc.

Many resources state that water utilization of textile processes depend on the desired end- product. The textile sector BREF [2] indicates that water consumption varies from 70 to 250 L/kg fabric depending on the techniques applied. According to a study [5], in Turkey "20–230 m^3 of water is required to produce 1 ton of textile fabric".

One of the common processes of textile industry is mercerization, which is found by John Mercer in 1844, to increase luster, strength and dyeability of the fabric. Mercerization gives the fabric's cross-section a circular shape. Caustic (NaOH) is commonly used for mercerization process. After caustic solution is applied while stretching the fabric, the fabric is rinsed with hot water. At the end of mercerization process, caustic and hot wastewater is produced. The wastewater produced is low in BOD and solids content [6].

Mercerization wastewater produced is high in volume and caustic content; therefore it shows quite alkali character. The aquatic organisms are quite susceptible to pH changes, and therefore discharge standards are set for this parameter, mercerization wastewater requires treatment. This treatment is commonly by neutralization which requires the use large amount of acidic addition. An alternative method is the recovery of caustic in the wastewater with the application of evaporation. According to Integrated Pollution Prevention and Control Communique for Textile Industry[2] Communiqué, evaporation can be done as follows: "caustic recovery by evaporation is done by first eliminating coarse particles with rotary filters or pressurized micro-filtration. Later, the wastewater is evaporated by passing steam from the condensers. Once NaOH is separated from the water, solution obtained at the end is purified by settling or addition of hydrogen peroxide, color is also removed during purification”.

Although this process of caustic recovery by evaporation is considered as a better solution, or as a BAT, its environmental impacts are not clear. There are no published studies in the literature that evaluate the effects evaporative caustic recovery process.

Being aware of adverse environmental impacts of industrial activities; United Nations Conference on Environment and Development (UNCED) in Rio in 1992, has discussed sustainable development concept ("Development that meets the needs of the present without compromising the ability of future generations to meet their own needs [41].") that first appeared in 1987, for the first time and has rapidly gained importance since then. Environmental management was another remark of this meeting since “sustainable development” was not possible without a smart resource allocation. Significance of environmental management has been increasing day by day since it is strongly related to decision making. Decision making procedure requires extensive analysis and some tools are used to make a healthy decision. For environmental management aspect, decision makers use some tools in order to make the best decision. One of these tools is Life Cycle Assessment (LCA). LCA helps the user by describing the environmental effects of a product or process during its lifecycle, calculating material and energy requirements, emissions to air/water/soil [7]. And also, LCA helps the decision maker to choose the process with lower energy

---

[2] Integrated Pollution Prevention and Control Communique for Textile Industry Communiqué, Official Gazette dated10.03.2015 Numbered 29291

demand, the materials which are easier to be degraded in the environment or less damaging to the environment by evaluating, comparing the alternative processes –if exists through the lifecycle of the process/material.

At the end, user can display the environmental impacts of a product or process and choose the most proper one among the options.

International Organization for Standardization (ISO) defines LCA as "compilation and evaluation of the inputs and outputs and the potential environmental impacts of a product system throughout its life cycle" [7]. LCA consists of four parts: goal and scope definition, inventory analysis, impact assessment and valuation. Definition, goal and scope step determines why the study is done by asking questions such as "How does evaporating mercerizing wastewater damage the environment?" After that, functional unit can be determined in order to equalize differences; in this case the functional unit is per kg of mercerization wastewater. And system boundaries are needed to define the limits such as "from cradle to grave", or from raw material extraction to reuse. Inventory step helps to compile and quantify data, estimate of environmental burdens. The result is found through measure of indicator of impact. The main concern is quantification, data and calculation. Impact analysis converts the result of inventory analysis into environmental effects such as climate change, toxicity etc. There are several impact categories; choice of these categories is made based on guides and software. In order to get a meaningful result, most relevant impact categories should be chosen. That is the reason of using methods such as Traci, IMPACT2002+, and eco-indicator 99, CML 1992 etc. Valuation step represents the result in a single environmental score.

1.1 Objective and Scope of the Study

The objective of the present study is to evaluate evaporative caustic recovery process in terms of its life cycle effects and to compare it with the conventional end-of-pipe treatment option. For data collection purposes, two different textile factories were visited in Kayseri (Study Plant 1) and Denizli (Study Plant 2). The Study Plant 1 produces denim fabric while the Study Plant 2 produces fabrics, mostly for home textiles. The Study Plant 1 was visited for observatory purposes while the Plant 2 was the one that local inventory data was gathered. To this end, the LCA tool "SimaPro software" is used adopting the inventory data collected from Study Plant 2. Evaluated data belong to years 2012, 2014 and 2015. IMPACT2002+ life cycle impact assessment methodology is used for assessing impacts.

Comparison of evaporative recovery with end-of-pipe treatment is done in three scenarios based on fuel used for steam production which is required in evaporation. Evaporation done with steam which is produced with heavy fuel oil, light fuel oil and natural gas are compared with end-of-pipe treatment.

In addition to LCA, Net Present Value (NPV) analysis is done to develop an understanding regarding the profitability of the suggested evaporative recovery method over conventional end-of-pipe treatment.

In the present thesis, background information about textiles industry and life cycle analysis, environmental issues related to textiles industry and economic analysis are given in Chapter 2. Using the information given in Chapter 2, Chapter 3 explains how data are used and how calculations are done. Then, results of the study are evaluated in Chapter 4 and summarized in Chapter 5. Some future recommendations related to the study are given in Chapter 6. This study is the first study that evaluates environmental impacts of evaporative recovery of mercerization wastewater, so called "weak lye" and assesses its profitability.

CHAPTER 2

BACKGROUND

2.1. TEXTILE INDUSTRY

Textile industry is an extensive industry. The end products are various: clothing, carpets, leather, home textile products like towels, and industrial products such as glass fibers, filters etc. Generally the first step is forming yarns from fibers. Fibers can be natural or manmade.

Natural fibers are grouped in two: animal-derived and herbal. Herbal fibers are obtained from roots, leaves, fruits, seeds and trunk; while animal derived fibers are obtained from leather, exudate(such as silk) and they can be derived from minerals.

Manmade fibers can be imitated, synthetically and inorganically. The general process is to make yarn from fibers, produce fabric from yarn and produce the desired end product. In Figure 1, the flow chart is given for cotton processing textile mill to better illustrate the flow of the processes.

2.1.1. Fiber Preparation

Before the fibers are processed into yarns they should undergo some treatments. They are opened, cleaned and blended. These processes are different for each type of fiber.

For example cotton is separated from the seeds in it, the impurities such as leaves are removed (ginning), opened and baled. Later in the mill, bales are further opened, blended; this process is called “carding”, where cotton is disentangled.

The most significant properties desired in the fibers are: “fiber length, fiber fineness, stretching and rupture elongation, quality of twists, quality of surface, dyeability, and ability of absorbing moisture, static electrification, and chemical properties” [9].

2.1.2. Yarn Production

The continuous cotton filaments are spun, this operation is generally dry. The fibers might be 100% cotton or they can be blended with other kinds of fibers such as man-made ones, or wool. The proportions are determined according to the desired end product. The spun yarn is winded on bobbins. The yarn can be further shaped or texturized if desired [10].

Quality factors of yarn are:” unevenness of yarn, neps, thin section, thick section, yarn count, winding, winding variation, tensile strength, tensile strength variation” [9].

2.1.3. Fabric Production

Fabric is produced in two ways: knitting and weaving. The raw material for these processes is yarns. Woven fabric is obtained by assembling yarns together on a loom.

Previous to weaving, warping and sizing are required. During warping, the yarns are wound on beams. This process does not require any agents. However sizing requires some auxiliary agents in order to protect the yarns. Sizing agents can be grouped in two: native polysaccharides and fully synthetic polymers. Native polysaccharides that are generally used are: starch and derivatives, cellulose derivatives, galactomannans, protein derivatives. Fully synthetic polymers are: polyvinyl alcohols, polyacrylates, polyvinyl acetate, polyester. The type of sizing agents to be used depends on type of the fiber [2].

Knitting does not require any agents, but only electricity. “Knitted fabric is obtained by knotting yarn together with series of needles” [2].

2.1.4. Pretreatment

Pretreatment is done for many purposes: to remove impurities, improve uniformity, affinity for dye-stuffs, wetting capacity, ensure relaxation of tensions in synthetic fibers.

Impurities are removed since they impair efficiency of finishing processes and not to damage fiber uniformity. Therefore, an appropriate pretreatment depends on:

- Type of fibers (manmade or natural)
- Machines (continuous, semi continuous)
- The chemical agents used (enzymes, washing, wetting agents etc.) [10].

Pretreatment of cotton includes many processes which are namely:

- Singeing
- Desizing
- Scouring
- Mercerizing
- Bleaching

Some steps are obligatory while some pretreatment processes are applied to only some kinds of fibers or depending on the desired end-product. For example, desizing is only applied to woven fabric.

2.1.4.1. Singeing

The fabric is not perfectly smooth after production. Hence it is passed through a gas flame. It is done to obtain satisfactory result in dyeing/painting processes and avoid "frosting" effect. After singeing, some amount of cooling water is required. The emissions from this process are dust particles, organic compounds and odor [2].

2.1.4.2. Desizing

Sizing agents impair finishing processes and they are not needed in the following processes, therefore they should be removed. Desizing methods depend on the type of fabric and kind of agent to be removed. There are four types of desizing processes:

- Thermal desizing
- Enzymatic desizing
- Oxidative desizing
- Desizing of water soluble sizes by washing

Thermal desizing is applied to glass fabrics; the fabric is heated up to 450˚C. Size agent is burnt. Enzymatic desizing, also known as classical desizing, is removing sizing agents by the help of enzymes. Oxidative desizing is less preferable since it is hard to avoid damaging the fabric during oxidation. This type of desizing requires alkali treatment. If the sizing agent is water soluble, desizing method would be washing [10].

2.1.4.3. Scouring

Scouring, also known as boiling off, aims to remove impurities such as proteins, waxes, fat etc. If scouring is done after desizing, the purpose is to remove residual size and desizing agents. Scouring can be done with other treatments (bleaching, desizing) or can be done as a separately [10].

2.1.4.4. Mercerizing

Silk is the most demanded fiber for being strong; however its production is very costly. Affording silk fabric hardly, people tried to find ways of imitating silk. Mercerization process gives the fabric silk-like properties. It can be applied both to fabric and yarn.

Found by a British chemist, John Mercer in 1844, mercerization process is named after him. He noticed the chemical properties of cotton changed when the fabric is contacted with high concentrations of caustic (approximately 300 g/L). The factories use a unit called Baume (Bé) for measuring amount of caustic rather than concentrations. Baume is measure of a solution's specific gravity relative to water. It is used to correlate to the percentage concentration (%w/w); both for liquids heavier/lighter than water. Distilled water is accepted as 0˚Bé. According to data obtained from the factories, 47 ˚Bé caustic solution is used for mercerization; at the end of mercerization process 11 ˚Bé wastewater is produced and sent to evaporation unit. During mercerization process a set of chemical reactions occur. Cellulose in cotton is involved in several chemical reactions.

Cellulose + NaOH ↔ Cellulose-OH + NaOH (1) Addition

Cellulose-OH + NaOH↔CEL-ONa + H_2O (2) Substitution

CEL-ONa: sodium cellulosate

After the reactions, properties such as increased luster, dyeability, absorbtivity, affinity for dyestuff (lowering use of dye-stuff), and strength are observed. However these changes occur depending on the sequence of application of the process as indicated in Figure 2.

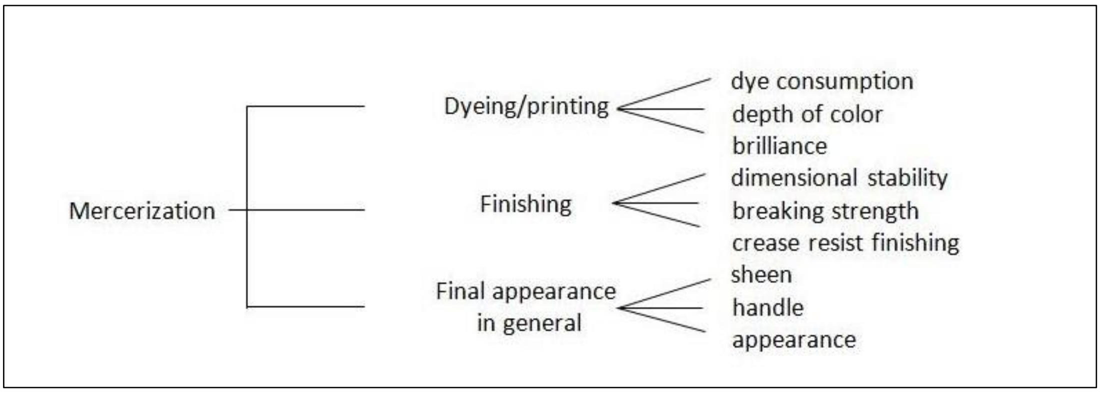

Figure 2. Effects of mercerization regarding sequence of application [10]

However, these effects might change according to sequence of application. Mercerization can be applied at various points during pretreatment [10]:

- “On grey fabric: fabric is dry before carrying out mercerizing process. This can be advantageous since introduction of agents used at other stages, dust and impurities found in cotton do not occur at this stage”.
- “On desized material: Sizing agent is removed essentially. Impurities in cotton cause contamination in lye in this stage, too”.
- “On scour boiled material: one of suitable stages for mercerizing. Fabric should be well-rinsed to avoid differences in caustic. This stage is eliminating problems faced during mercerizing after bleaching such as loss of degree of whiteness and reduction of absorbency”.
- “On bleached material: after bleaching the dyeing affinity and brilliance is at maximum, lye won’t be contaminated. The breaks, folds and physical faults are covered after mercerization”.
- “On dyed material: the dye must be stable to caustic, otherwise affinity will be lowered and dyeing process will not be a satisfactory one. Tensile strength of the fabric will increase and fabric will be more suitable for finishing processes”.

Luster is a result of light. Cotton becomes smoother as a result of mercerization and reflects light better. In the electronic microscope image in Figure 3, it is seen that caustic gives the cotton fibers a cylindrical shape.

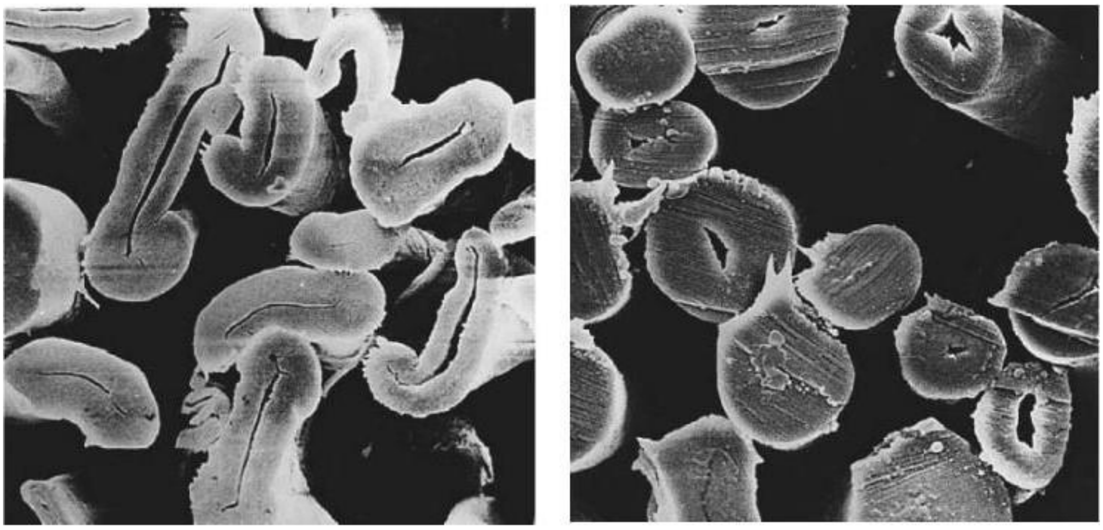

Figure 3. Electronic microscope image of cotton fibers before (on the left) and after (on the right) mercerization [10]

The most important parameters of mercerization are:

- Twaddle (concentration of NaOH)
- Tension
- Temperature
- Time

Caustic with concentration around 270-330 g/L is best for the dry fabric mercerization. At lower temperatures higher shine can be obtained. Cotton can swell to maximum degree at 12-15^{0}C, however complete penetration can be obtained around 50-60^{0}C (hot mercerization), however with lower swelling. Optimum shine is obtained with hot mercerization. 30-60 seconds are enough for caustic solution to penetrate into cotton fibers. To obtain penetration of caustic solution to fibers some methods like using wetting agents, vacuum with suction caps, ventilation, heating the fabric prior to mercerization are applied. Reaction time can be determined by “glass point”. This point can be reached when the complete fabric becomes transparent as glass [10]. Higher temperatures require less time to reach glass point. Tension is applied in order to prevent shrinking. The length is increased by 1-2% after mercerization [9].

Mercerizing machines profile is dependent on type of substrate (i.e. woven, knit, yarn). The functional parts of a mercerizing machine for woven fabric are as shown in Figure 4:

- Impregnation zone for wet application
- Reaction zone where swelling occurs
- Stabilization zone where tension is applied and lye is diluted
- Washing and neutralization zone

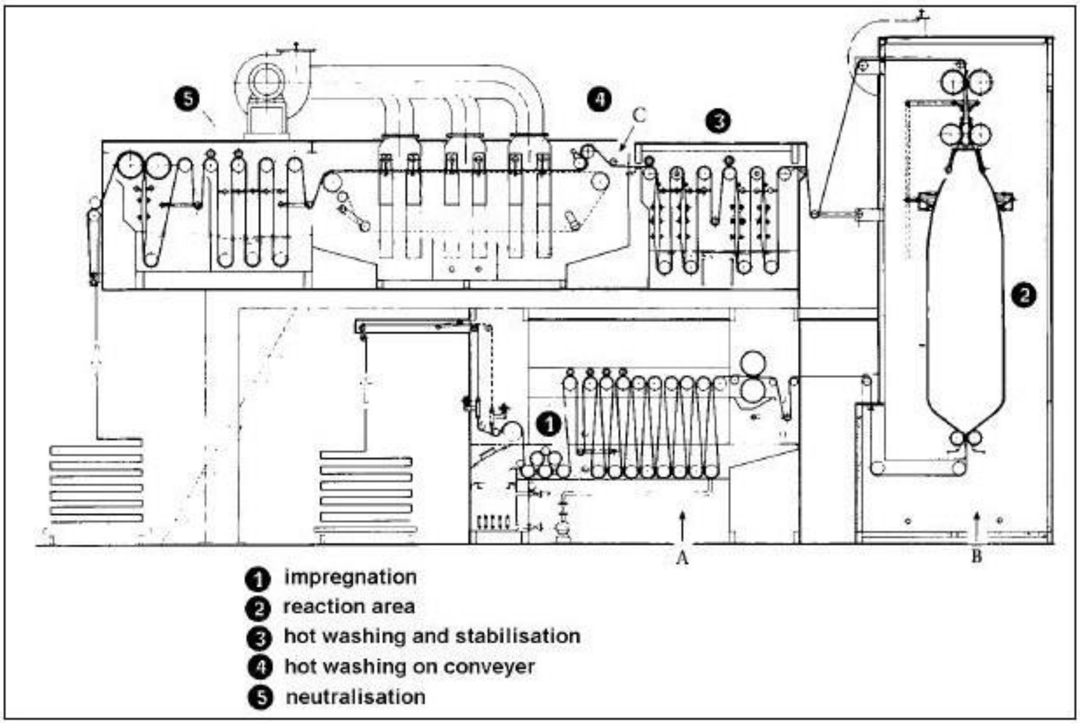

Figure 4. Example of mercerizing equipment for knitted fabric [2]

There are three types of mercerization process:

- Mercerization (stretched)
- Caustification (without stretching)
- NH_3 mercerization

Mercerization (stretched): This one is the most common mercerization process, where NaOH solution is used. Cotton fabric or yarn is contacted with NaOH solution for 40-50 seconds, the concentration of solution is 270-300 g NaOH/L which makes 170-350 g NaOH/kg. Another important parameter for mercerization is temperature. If luster is aimed, the temperature should be around 15-18^{0}C if the other parameters are more important, then the temperature can be higher (for example another common temperature which mercerization is realized is 50-60 ^{0}C).

Hot mercerization is also used; the fabric or yarn is contacted with solution which is almost at boiling point while it is being stretched. After contacting, the fabric/yarn is cooled to room temperature and washed while being stretched.

In order to provide penetration of caustic in a homogenous way; wetting agents are used. Non-ionic surfactants and mixture of sulphonates with phosphoric esters are commonly used wetting agents. After mercerization, the fabric/ yarn is neutralized with 5% citric acid solution [2].

Caustification (without stretching): The material is contacted with lower concentration of NaOH solution which is around 45-190 g/L, at 20-30^{0}C, without stretching. This method provides better absorption of dyestuff. Therefore lower the use of dyes.

NH_3 Mercerization: Cotton yarns and cotton fabrics can be contacted with waterless liquid ammonia, as an alternative to caustic solution. The effects are like caustic mercerization, however fewer luster is obtained. Residual ammonia is removed dry-hot process followed by evaporation. This method is not very common. A few plants are reported to be using this method in Europe.

2.1.4.5. Bleaching

During bleaching, textiles are chemically treated in order to lighten or remove the tinting contained in grey fabrics. Bleaching is a chemical process where natural tint is destroyed with oxidative processes. Sometimes fluorescent brightening agents are used; bleaching can be combined with other processes such as scouring, desizing and dyeing, according to the desired end product.

Bleaching can be applied to all kinds of products: knitted fabric, woven fabric and yarns. Since bleaching is a chemical process, some chemical agents are used. The most common bleaching agents are:

- Hydrogen peroxide (H_2O_2)
- Sodium hypochlorite (NaClO)
- Sodium chlorite ($NaClO_2$) [2].

2.1.5. Dyeing and Printing

Dyeing materials are divided into three groups considering the application method.

First group is called fiber reactive dyes which can be acidic, basic, reactive, direct and mordant. Acidic dyes, used on nylon and wool, they are rarely used. Direct dyes are used on cotton. Mordant dyes are reacted with metal salts prior to dyeing. Reactive dyes give reaction with the hydroxyl groups in cellulose. Second group is called vat dyes. Sulfur dyes are in this group. This group of dyes required to be made insoluble by oxidation before application. And, the third group is named as special dyes which are disperse, solvent, natural dyes and pigments.

Dyeing can be done in continuous or batch form. Continuous dyeing is performed by passing the material through a dye-bath. Later steaming is applied on the material in order to fix the dye. Then the material is washed in order to remove excess dye. Another method is batch dyeing. This method requires longer time and larger volume. Examples of batch dyeing machines are beck, jigs, beam package, jet.

Some auxiliary chemicals are used to fix dyes on the material. And de-foaming agents are used to prevent foaming caused by auxiliary agents. Also salts are used in order to retard rate of dyeing.

Printing paste is thick and viscous to prevent unsatisfactory results. Paste is transferred onto material by using different methods such as rotary screens, flat screen etc. After applying the paste, heat treatment is done to fix the colors and color patterns.

2.2. ENVIRONMENTAL ISSUES RELATED TO TEXTILE WASTEWATERS

2.2.1. Wastewater Producing Processes

Textile industry produces solid and liquid wastes as well as gas emissions. Among the waste types, liquid waste production is the highest therefore huge amounts of wastewater production occur. The volume and the components of wastewater are specific to desired end product, process and the equipment used. The components of wastewater contribute to high pollution loads. Especially wet processes employ variety of chemicals and large volumes of water. Examples to processes causing wastewater production are: washing, sizing, desizing, bleaching, rinsing, mercerizing, dyeing and finishing [12]. There are many types of fibers, dyes, auxiliary agents, finishing products that produce wastewaters of chemical complexity and diversity which makes the wastewater hard to treat in conventional wastewater treatment plants. Therefore the wastewater treatment plant design should be done plant specific. According to Cooper [12]; the wastewater quality and quantity depends on four factors:

- Type of fiber
- Unit operations constituting the overall textile finishing process
- Process chemicals
- Recycle and conservation procedures in force

The chemical composition of wastewater can change due to shifts in needs of consumers. For example, if bright colors are currently popular, that leads use of reactive and azo-dyes. The regulations also may cause changes in wastewater composition such as German ban in 1996 on consumer goods containing azo-dyes due to azo-dyes yielding carcinogenic aromatic amines [13].

It should be known that generalizations might have little specific relevance. Textile wastes generally are high in BOD, temperature and TSS, and highly colored, alkaline. The pollutants in textile wastewater are: COD, BOD, TSS, TDS, VSS, oil and grease, pH, color, nitrogen, phosphorus, metals, sulfur compounds, TOC, Cl^-, TDS, alkalinity, surfactants, hardness, AOX, turbidity [6]. Table 1 summarizes emissions to air and water and their residual wastes for different processes of the textile industry.

Table 1. List of some of the waste materials generated at each level of cotton textile processing [3]

Process	**Air Emissions**	**Wastewater**	**Residual Wastes**
Fiber preparation	Little or no air emissions generated	Little or no wastewater generated	Fiber waste; packaging waste; hard waste
Yarn spinning	Little or no air emissions generated	Little or no wastewater generated	Packaging waste; sized yarn; fiber waste; cleaning and processing waste.
Sizing	Volatile organic compounds	BOD; COD; metals; cleaning waste, size	Fiber lint; yarn waste; packaging waste; unused starch-based sizes
Weaving	Little or no air emissions Generated	Little or no wastewater generated	Packaging waste; yarn and fabric scrapes; off-spec fabric; used oil
Knitting	Little or no air emissions generated	Little or no wastewater generated	Packaging waste; yarn and fabric scrapes; off-spec fabric
Tufting	Little or no air emissions Generated	Little or no wastewater generated	Packaging waste; yarn and fabric scrapes; off-spec fabric
Desizing	Volatile organic compounds from glycol ethers	BOD from water-soluble sizes; synthetic size; lubricants; biocides; anti-static compounds	Packaging waste; fiber lint; yarn waste; cleaning materials, such as wipes, rags and filters; cleaning and maintenance wastes containing solvents

Table 1. (Cont'd)

Scouring	Volatile organic compounds from glycol ethers and scouring solvents	Disinfectants and insecticide residues; NaOH; detergents; fats; oils; pectin; wax; knitting lubricants; spin finishes; spent solvents	Little or no residual waste generated
Bleaching	Little or no air emissions Generated	Hydrogen peroxide, sodium silicate or organic stabilizer; high pH	Little or no residual waste generated
Singeing	Small amounts of exhaust gasses from the burners	Little or no wastewater generated	Little or no residual waste generated
Mercerizing	Little or no air emissions Generated	High pH; NaOH	Little or no residual waste generated
Heat setting	Volatilization of spin finish agents applied during synthetic fiber manufacture	Little or no wastewater generated	Little or no residual waste generated
Dyeing	Volatile organic compounds	Metals; salt; surfactants; toxics; organic processing assistance; cationic materials; color; BOD; sulfide; acidity/alkalinity; spent solvents	Little or no residual waste generated
Printing	Solvents, acetic acid from dyeing and curing oven emissions; combustion gasses; particulate matter	Suspended solids; urea; solvents; color; metals; heat; BOD; foam	Little or no residual waste generated
Finishing	Volatile organic compounds; contaminants in purchased chemicals; formaldehyde vapor; combustion gasses; particulate matter	BOD; COD; suspended solids; toxics; spent solvents	Fabric scrapes and trimmings; packaging waste
Product fabrication	Little or no air emissions Generated	Little or no wastewater generated	Fabric scrapes

2.2.2. Effluent Characteristics of Mercerization Wastewater

Mercerization process utilizes caustic solution (NaOH) solution in order to treat the fabric. Later, the fabric is washed with weak acid solution. Wastewater from mercerizing has alkaline nature; it is high in pH, while BOD and solids content is low. Large mills generally treat wastewater from mercerization process and reuse the caustic, thus lower the load to waste stream [12]. Another solution for the treatment of mercerization wastewater is neutralization with another stream originating from another textile process that produces acidic wastewater, thus obtaining less alkaline and acidic wastewater. Environmental problems are mainly rising from wastewater discharge. In a study [36], it has been found out that primary water consumption is 80-100 m^3/ton finished textile, and discharge is 115-175 kg of COD/ton finished textile. Wastewater characteristics are generally as follows: variety of organic chemicals, color, heat, high suspended solids, salinity, chemical oxygen demand, low biodegradability, soluble substances. The effluents vary depending on the desired end product, nature of the raw material, machinery etc. The study has found out that main pollutants from mercerization process are: pH, TSS, chlorides, COD, fixed residual, BOD_5, NO_2^-, NH_4^+, H_2S, and NO_3^-. Their average values are given in the

Table 2.

Table 2. Compositon of mercerization wastewater [36]

Pollutant	**Value**
pH	10.8
NO_3^-	9.4 mg/L
TSS	105.2 mg/L
Chlorides	119.5 mg/L
COD	2788.2 mg O_2/L
H_2S	1.3 mg/L
NH_4^+	8.5 mg/L
NO_2^-	2.7 mg/L

Table 2. (Cont'd)

Fixed residual	3877.2 mg/L
BOD_5	300 mg O_2/L

According to Water Pollution Control Regulation of Turkey[3], discharge standards for cotton finishing processes are given in Table 3.

Table 3. Discharge limits for cotton textile wastewater (From Water Pollution Control Regulation- Table 10.3)

Parameter	**Unit**	**Composite Sample 2 h**	**Composite Sample 24 h**
COD	mg/L	250	200
TSS	mg/L	160	120
NH_4-N	mg/L	5	-
Free Chlorine	mg/L	0.3	-
Total Chrome	mg/L	2	1
S^{-2}	mg/L	0.1	-
Sulfite	mg/L	1	-
Oil and Grease	mg/L	10	-
Fish Toxicity Dilution Factor	-	4	3
pH	-	6-9	6-9
Color	Pt-Co	280	260

[3] Water Pollution Control Regulation, Official Gazette No: 25687 dated 31.12.2004

2.2.3. Treatment Methods and Reuse Opportunities

As it was stated before, the textile industry utilizes vast amounts of water. The amount of water utilized changes according to the desired end-product but the average range per ton of fabric can be given as 20-230 m^3 [15]. While the supply for water is constant, the need of fresh water for industrial use increases. The increasing demand for water and valuable substances has urged new solutions and technology. The world's main focus is on recycling the industrial wastewater, reusing the heat, by-products and the chemicals utilized in processes.

Being aware of the fact that water sources will not be enough to meet the demand in the future, many countries have taken some measures to minimize their impact on water sources caused by the industries. The primary approach was called "end-of-pipe" where the pollutants were treated or disposed which required investments, that is considered as financial burden. The amounts of pollutants and treatment costs have increased while discharge standards have decreased due to developing awareness of consumers about environmental issues. Also end-of-pipe approach has been affecting the environment adversely due to its adverse effects. This situation led producers to seek other approaches to make environmentally friendly products. Thanks to the new approach, which is called "cleaner production", material loss would be prevented and amount of waste would be reduced. This approach later is supported by replacing some raw materials with more environment friendly raw materials, reducing the need for water and energy by using them more efficiently. Cleaner production has become significant and has been considered as a strategic tool.

The European Union the Integrated Pollution Prevention and Control Directive (IPPC, 96/61/EC) came into force for the first time in 1996, which adopts lifecycle approach besides, considers pollution prevention and protecting the environment by ensuring the industrial site is in baseline condition which is determined during permitting [16]. This Directive was later revised and given the name "Industrial

Emissions Directive" (IED, 2010/75/EU). According to IPPC/IED, permit conditions are set by considering BAT given in the sectoral BREFs and emission limit values (ELVs) achievable upon implementation of BATs, so called "BAT associated emission limit values, BATAEL". The BATs are defined for all sectors as: "the most effective and advanced stage in the development of activities and their methods of operation which indicate the practical suitability of particular techniques for providing in principle the basis for emission limit values designed to prevent and, where that is not practicable, generally to reduce emissions and impact on the environment as a whole". The Directive aims "high level protection of environment as a whole" [2].

In order to ensure protection of the environment, some measures that can be applied. Examples of recycling and reclamation of textile industry are:

- "Direct re-use of non-contaminated water (using cooling water for general purposes),
- Using high quality process water in a low-quality process such as using final rinse water in first rinse,
- Treating and reusing wastewater for reuse in other processes,
- Using treated wastewater and recycling the effluents (chemicals, by-products, water, heat energy) for direct use in the process,
- Mixing wastewater from all processes, treating and reusing" [17].

Turkey has started to adopt EU legislation for harmonization purposes. For that reason, Integrated Pollution Prevention and Control Communique for Textile Industry is published. This communique was revised on 10.03.2015 and published in the Official Gazette numbered 29291; the revised version states that facilities that do mercerization above 1 ton/day are required to recover alkali from wastewater since recovery process facilitates solution of the problems regarding salinity and conductivity. The communique offers two solutions for recovery one of them is to evaporation and the other one is membrane filtration (NF+RO and evaporation is employed).

2.2.4. Caustic Recovery from Mercerization Unit

As caustic is a basic compound, it raises pH of the aquatic environment when discharged. Higher pH values cause deaths of adult fish and invertebrates also damages juvenile fish life. Also damages the skin of the fish by chapping, damages eyes and fish fail disposing metabolic wastes. When pH is high, some substances such as ammonia become more severely toxic. These are the reasons why highly alkaline water is not desirable. Therefore water should be treated if it is of alkaline nature.

The textile sector BREF Document's "4.5.7" numbered chapter is about recovery of alkali from mercerizing which is stating that the driving force for recovering the caustic is, its alkali nature and economic losses due to not considering reuse of caustic. Once the textile substrate leaves stabilization tank, it is sent to rinsing tanks in order to remove caustic. This rinsing water is called weak lye (diluted caustic solution) and it can be concentrated with evaporation. NaOH solution obtained at the end can be recycled to the process.

The concentration of typical weak lye is usually 5 - 8 °Bè (30 - 55 g NaOH/L) and its concentration can be increased to 25 - 40 °Bè (225 - 485 g NaOH/L), depending on the mercerizing process applied. When mercerization is carried out on the greige dry textile substrate (raw mercerization) it is not possible to obtain concentration of caustic higher than 25 - 28 °Bè. However, after non-raw mercerization process, it is possible to achieve concentration of 40 °Bè. "In raw mercerization, the concentration of impurities is significantly higher, as is viscosity, which makes it difficult to reach higher concentrations (circulation in evaporators is disturbed) [2]."

Evaporation is done by using steam to heat the weak lye (11 Bé caustic solution) by passing steam through the heat exchangers in the evaporator, Figure 5 illustrates evaporator's stages. Separated and heated water is passed through the system. At the end steam becomes condensate; weak lye is separated in two parts: strong lye and distillate.

The textile sector BREF document states that "the higher the number of stages for evaporation, the more often the heat is re-used, the lower the steam consumption and, therefore, the running cost. However, investment cost obviously increases with the number of stages" [2]. The technique is applicable for colored alkali water after applying oxidation to remove color. Main driving forces for caustic recovery are: high alkali content of waste water and economic aspects of caustic losses.

According to a study [18], the concentration of caustic solution leaving mercerization unit is 4%, and after evaporation solution of 20% caustic solution can be obtained. At the Study Plant 2, concentration of caustic solution leaving mercerization unit is 7.3% and 30% caustic solution is obtained after evaporation.

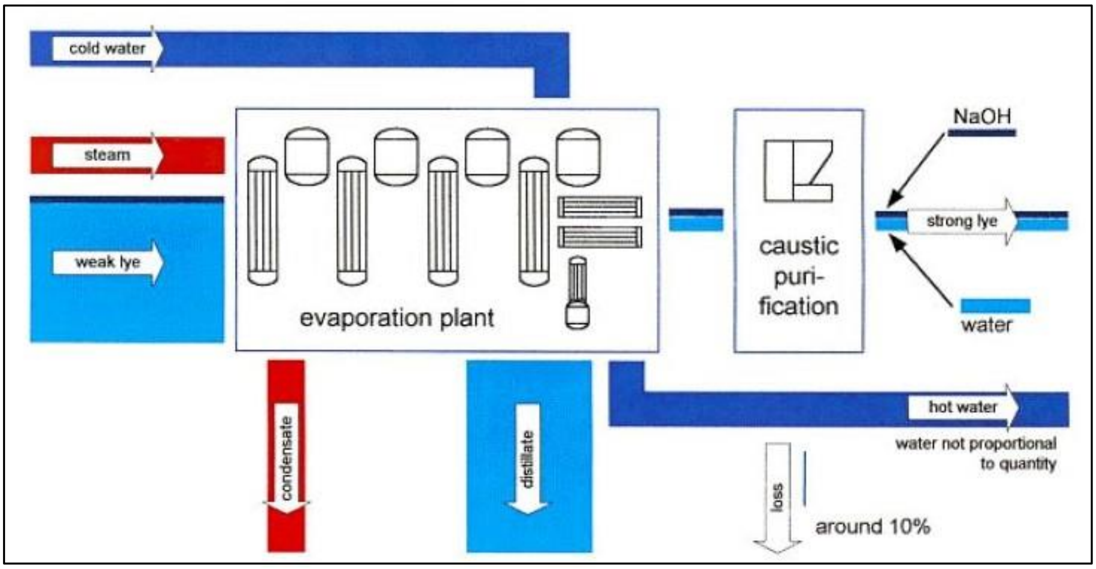

Figure 5. Scheme of evaporation plant for caustic recovery [2]

2.3. LIFE CYCLE ASSESSMENT

LCA is used to determine short and long term effects and helps the user assess the environmental impacts of a product or process. An LCA helps the decision makers make a selection among product or process that has least impacts on the environment.

LCA considers many aspects such as chemical use, electricity use, raw material use, fuel use, emissions to air, water and land and environmental impacts of such emissions. In LCA the entire life cycle can be considered for a product/process/activity, from raw material obtaining to final disposal.

As stated in ISO 14040:2006 document [7], an LCA assists in:

- Product development and improvement

- Decision making (for industries, governmental and non- governmental organizations)
- Marketing
- Environmental performance indicators selection
- Planning (on production stages, process design, strategy etc.)
- Generation of understanding the trade-offs

As stated before, an LCA study has four steps which are namely:

- **Goal and scope definition**: planning part of LCA, product/process/activity is described, boundaries are set, expected environmental effects are reviewed
- **Inventory analysis**: material and energy balance calculation is done, energy, raw material, and water requirements are quantified and also environmental releases are identified & quantified
- **Impact assessment**: classification, characterization and valuation and impacts evaluation is done; used energy and materials' effects on ecology are identified
- **Interpretation:** inventory analysis results are evaluated; a clear understanding is established

The interactions between these steps are shown in the Figure 6.

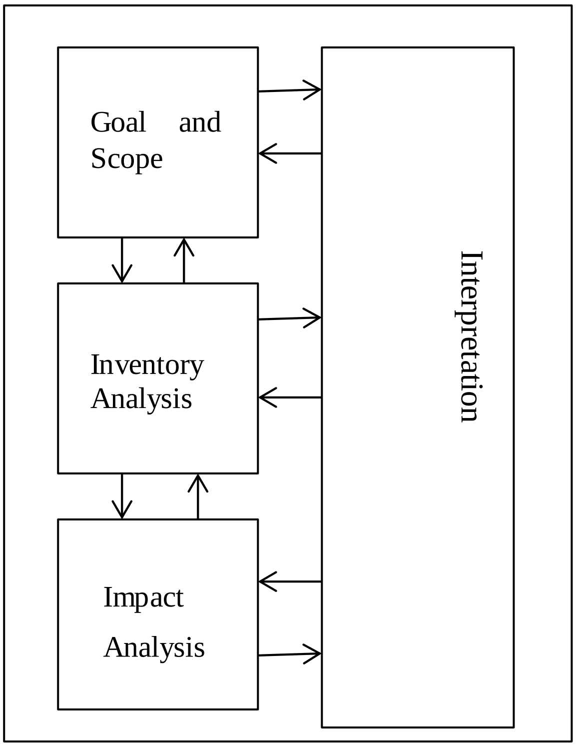

Figure 6. Life cycle assessment framework [7]

Textile industry has been increasingly using life cycle assessment, recently. Environmental impacts of textile-related products and/or processes have been considered in several studies. As stated in one of these papers, there is a growth in LCA studies, however in scientific literature there is not enough LCA studies presented [22]. There are some examples of these studies such as: life cycle of cotton trousers [23] to benchmark materials used in yarns such as cotton, polyester, nylon, acryl, elastane [22], to compare methods of dyeing, to get to the roots of problem and understand the impact of water utilization of cotton and land occupation of the cotton fields, compare recycled material with use of virgin material [19], fate modeling [21], compare methods used in processes such as bleaching, impacts of using some materials during processes (cotton, freshwater etc.) [24], or assess the lifecycle of a textile product such as denim trousers, bathrobes, t-shirts etc.[25] and defining environmental profile of cotton and polyester cotton fabrics [20].

2.3.1. Goal and Scope Definition

Goal and scope definition is the step in which purpose and method are described. This is the first step where the system under assessment is defined by determining boundaries and setting the goal. Boundary determination is done in the thermodynamic sense by reviewing environment of the system. Relevance of the results highly depends on goal and boundary conditions.

The system is under consideration because of its products (i.e. outputs). In order to have the outputs, a system must have inputs (raw material, energy etc.) and then the boundaries can be set according to the needs such as cradle-to-grave, gate-to-cradle, gate-to-gate etc. Cradle-to-grave approach considers the materials from raw material extraction phase and follows it to the disposal of the product, which is also called total LCA. If the boundaries of the system are wider, there will be more burdens and impacts included. Cradle-to-grave approach is rarely used, cradle-to-gate or gate -to- grave approaches are more common and considers the life span from the production to factory which can also be called as partial LCA. Any stage can be considered as “gate”: manufacturing, transportation, distribution, use, recovery, reuse, recycling.

While deciding upon the approach, things can get a bit confusing. While producing milk, trucks are used for delivery. User has to decide whether to include the truck to LCA or not (Considering production of truck, steel needed, energy has to be obtained from fuels, and fuel extraction is needed and so on). At this point, user needs to decide including capital goods and their manufacturing and disposal.

There are three orders:

1. First order: “only the production of materials and transport are included” (this is rarely used in LCA).

2. Second order: “All processes during the life cycle are included but the capital goods are left out”.

3. Third order: “All processes including capital goods are included. Usually the capital goods are only modeled in a first order mode. So, only the production of the materials needed to produce the capital goods are included” [26].

Another issue to be defined under this topic is “system function” which enables the user make comparisons based on an equivalent unit that is called “functional unit”.

To illustrate, life cycle of evaporation of mercerizing wastewater considers “per kg of wastewater evaporated”. So the calculations can be done on this basis, caustic recovery per kg of wastewater evaporated.

2.3.2. Inventory Analysis

After the system boundaries have been determined, the user should define the list of inputs and outputs. In other means, the quantification of materials utilized such as raw materials, fuel, electricity etc.; releases such as solid waste, atmospheric emissions, waterborne emissions. Life cycle inventory (LCI) analysis can be beneficial in decision-making, comparing alternative materials for utilization in processes, considering environmental factors while developing regulations and limit/ban some certain substances. After inputs and outputs are determined, a flow diagram should be done to illustrate what goes in the “system” and goes out of the “system” within the “system boundaries” that were determined at the previous step. A general example of system with inputs and outputs is shown in Figure 7 with flow diagram for mercerization and evaporator.

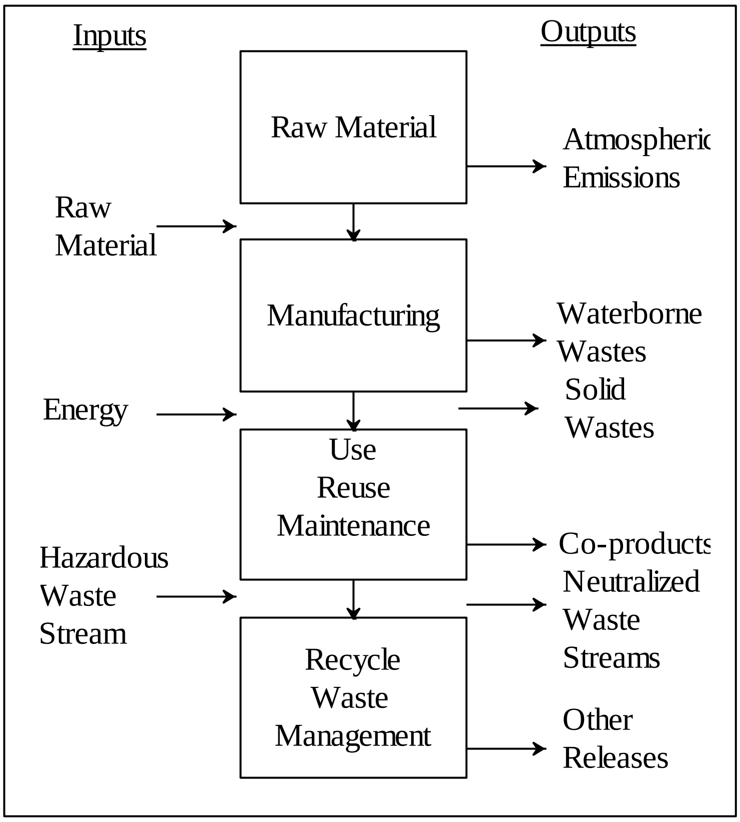

Figure 7. General illustration of a "system" [7]

Data collection is the next step. During this step data quality must be considered precisely, accurate data lead better decision-making. Data of good quality must be precise, complete, accurate, representative, consistent and reproducible [27]. Therefore, data sources play an important role. According to EPA Guidelines [27], data sources can be:

- Meter readings from equipment
- Equipment operating logs/journals
- Industry data reports, databases, or consultants
- Laboratory test results
- Government documents, reports, databases, and clearinghouses
- Other publicly available databases or clearinghouses
- Journals, papers, books, and patents

• Reference books
• Trade associations
• Related/previous life cycle inventory studies
• Equipment and process specifications
• Best engineering judgment.

Examples of data types include:

• Measured
• Modeled
• Sampled
• Non-site specific (i.e., surrogate data)
• Non-LCI data (i.e., data not intended for the purpose of use in an LCI)
• Vendor data

SimaPro has data quality indicators (DQI) which requires the user give information about data. Detailed information will be given in methodology chapter.

2.3.3. Life Cycle Impact Assessment

Life cycle impact assessment step is where the data collected in life cycle inventory step is explained in a meaningful way. Evaluation of environmental impacts and health effects of a product or process is done in this step. The impacts are calculated via "stressors". Since the impacts are caused by stressors which are set of conditions [27]. To illustrate, pesticides used for agricultural purposes might volatilize and soil releases volatile organic compounds that contributes to air pollution by producing tropospheric ozone. During Life Cycle Impact Assessment (LCIA), classification and characterization of such environmental effects are done.

Potential impacts are determined and category indictors of the potential impacts are calculated for each impact category.

To better illustrate, ISO 14040/44 states the steps that have to be taken are:

- Classification and characterization (obligatory steps)
- Normalisation, ranking, grouping and weighting (optional steps)

Optional steps are defined as [27]:

- "Normalisation –Calculating the magnitude of category indicator results relative to reference values",
- "Grouping –sorting and possibly ranking of the impact categories",
- "Weighting –quantitative comparison of impact potentials of the product or service",
- "Data quality analysis –better understanding the reliability of the collection of indicator results".

Emissions listed in inventory analysis are assigned to impact categories depending on their ability of contributing to several environmental problems. Characterization relates the inventory results to an "endpoint". This concept will be explained after the optional steps.

Depending on requirements of goal and scope determination some optional steps can be used [28]. If need be, normalisation is used for comparing environmental impact categories which are of different types but with the same unit. Normalisation yields two results: grouping and weighting. Grouping is a qualitative process where results are sorted and ranked. In weighting relative importance of impact categories are determined by a weighting factor.

LCIA employs two different modelling types which are called mid-point and end-point modelling. "Midpoints are considered to be a point in cause-effect chain of an impact category while endpoint reflects relative importance of an input or output" [29]. To illustrate better: endpoint-based approaches consider human health, ecosystem while midpoint based approach assesses reasons of endpoint categories: global warming, ozone depletion etc.

Due to the emissions from a factory, some gasses may contribute to global warming; result of the global warming is climate change which is the ultimate scenario for the situation. Also, ISO states that "indicators chosen close to the inventory have lower uncertainty" since they require less modeling for the environmental mechanism. Indicators near end-point have higher uncertainty but they are more understandable.

Table 4. Midpoint and endpoint impact categories listed [29]

Mid-point impact categories	**End-point impact categories**
Carcinogens	Human Health
Non-carcinogens	
Respiratory inorganics	
Ionizing radiation	
Ozone layer depletion	
Respiratory organics	
Aquatic ecotoxicity	Ecosystem Quality
Terrestrial ecotoxicity	
Terrestrial acid/nutrients	
Land occupation	
Aquatic acidification	
Aquatic eutrophication	
Global warming	Climate Change
Non-renewable energy	Resources
Mineral extraction	

LCIA methodologies link each LCI result with corresponding environmental impacts by using characterization factors (CFs). One of these methodologies is IMPACT2002+ which provides a basis for "a feasible implementation of a combined midpoint/end-point approach, linking all types of life cycle inventory results via several midpoint categories to several end-point categories" [29]. In Figure 8 and Table 4, the mid-point categories and corresponding end-point categories can be seen.

Scores for midpoint categories are represented in units of a selected reference substance and related end-point categories are expressed in DALY (Disability Adjusted Life Years), PDF.m^2.y (Potentially Disappeared Fraction of species over a certain amount of m^2 during a certain amount of year), kg $CO_{2\text{-eq}}$ and MJ (Mega Joule), respectively. Detailed explanation of midpoint and end-point categories will be done in the following parts of this chapter. IMPACT 2002+ method provides the following: "midpoint characterization factors, damage factors, normalized midpoint characterization factors and normalized damage factors" [32].

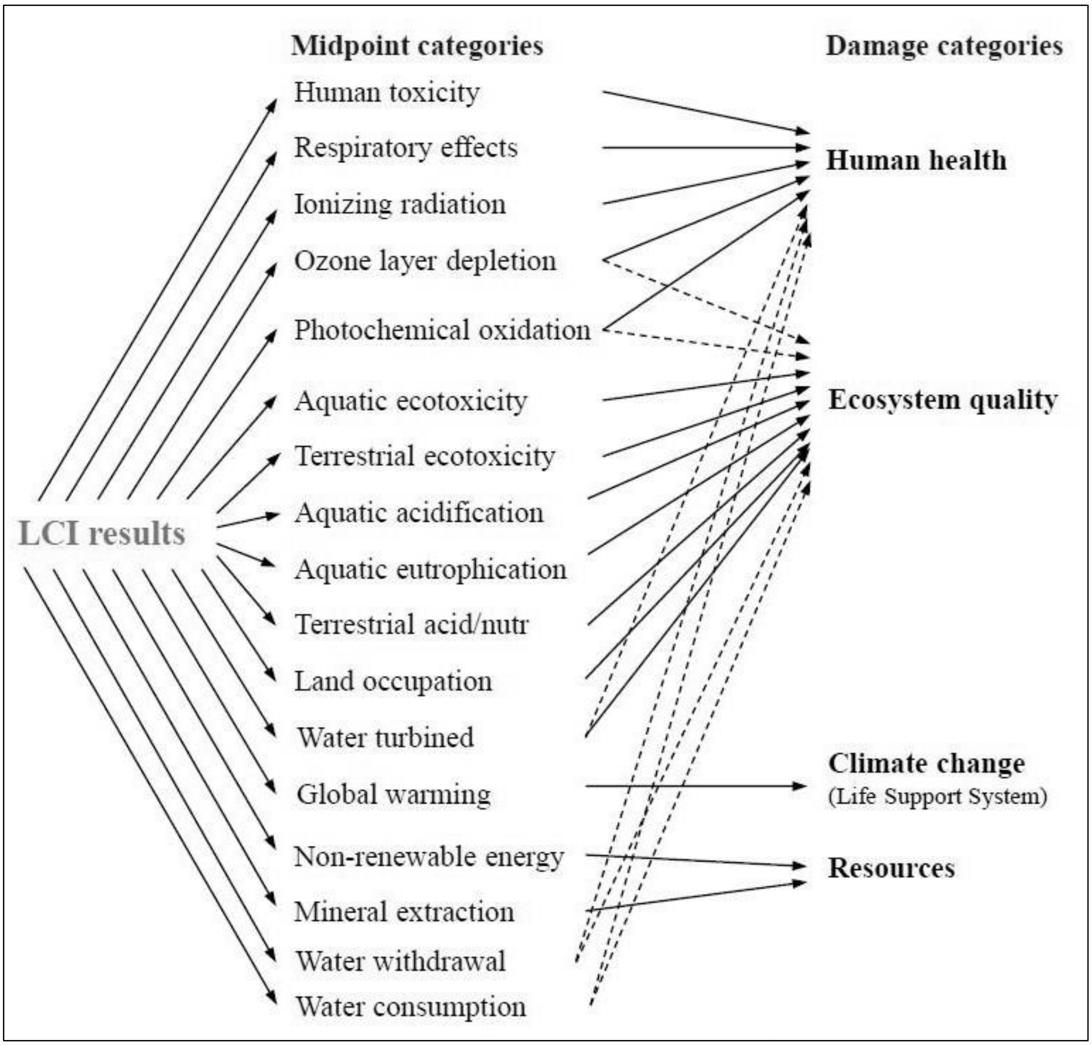

Figure 8. Midpoint categories and related end-point categories [32]

In Figure 8, impact pathways between midpoint and endpoint impact categories are shown. Dotted lines indicate relations that are not modeled due to missing knowledge or currently being developed or for avoiding duplication.

To illustrate the assessment characteristics for midpoint and end-point categories, their corresponding normalisation factors and application of IMPACT2002+,

Table 5 is prepared.

Table 5. Midpoint and end-point categories with corresponding normalized damage units [32]

Midpoint Category	Midpoint reference substance	End-point category	Damage unit	Normalized damage unit
Human toxicity (carcinogens + non-carcinogens)	kg Chloroethylene into air$_{-eq}$	Human health	DALY	Point
Respiratory (inorganics)	kg $PM_{2.5}$ into air$_{-eq}$	Human health		
Ionizing radiations	Bq Carbon-14 into air$_{-eq}$	Human health		
Ozone layer Depletion	kg CFC-11 into air$_{eq}$	Human health		
Photochemical Oxidation (Respiratory organics for human health)	kg Ethylene into air$_{-eq}$	Human health		
		Ecosystem quality	n/a	n/a
Aquatic ecotoxicity	kg Triethylene glycol into water$_{-eq}$	Ecosystem quality	$PDF.m^2.yr$	Point
Terrestrial ecotoxicity	kg Triethylene glycol into soil$_{-eq}$	Ecosystem quality		
Terrestrial acidification/nutrification	kg SO_2 into air$_{-eq}$	Ecosystem quality		
Aquatic acidification	kg SO_2 into air$_{-eq}$	Ecosystem quality		
Aquatic eutrophication	kg $PO_4{}^{3-}$ into water$_{-eq}$	Ecosystem quality		
Land occupation	m^2 Organic arable land$_{-eq}$ y	Ecosystem quality		
Water turbined	inventory in m^3	Ecosystem quality		
Global warming	kg CO_2 into air$_{-eq}$	Climate change (life support system)	kg CO_2 into air$_{-eq}$	Point
Non-renewable energy	MJ or kg Crude oil$_{eq}$ (860 kg/m^3)	Resources	MJ	Point

Table 5. (Cont'd)

Mineral extraction	MJ or kg $Iron_{-eq}$ (in ore)	Resources		
Water withdrawal	inventory in m^3	n/a	n/a	n/a
Water consumption	inventory in m^3	Human health	DALY	Point
		Ecosystem quality	$PDF.m^2.yr$	
		Resources	MJ	

The criteria to use a substance as a midpoint reference substance are: "an example with proven effects for regarding category, a generally accepted substance, a substance with relatively low uncertainties in the fate, exposure and effect modelization" [32].

$$\text{Midpoint} \xrightarrow{\text{CF}} \text{End-point}$$

Detailed explanations of units used in IMPACT 2002+ are given below [32]:

At midpoint level:

- ""kg substance s-eq" ("kg equivalent of a reference substance s") expresses the amount of a reference substance s that equals the impact of the considered pollutant within the midpoint category studies (e.g., the Global Warming Potential on a 100-y scale of fossil based methane is 27.75 times higher than CO_2, thus its CF is 27.75 kg CO_2-eq)" [32].

At end-point level:

- ""DALY" characterizes the disease severity, accounting for both mortality (years of life lost due to premature death) and morbidity (the time of life with lower quality due to an illness, e.g., at hospital). Default DALY values of 13 and 1.3 [years/incidence] are adopted for most carcinogenic and non-carcinogenic effects, respectively (Keller 2005). Note that these values replace the values of 6.7 and 0.67 calculated by Crettaz et al. (2002) and used in the previous versions of IMPACT 2002+ For example, a product having a human health score of three DALYs implies the loss of three years of life over the overall population” [32].

- ““PDF·m^2·y” is the unit to “measure” the impacts on ecosystems. The PDF·m^2·y represents the fraction of species disappeared on 1 m^2 of earth surface during one year. For example, a product having an ecosystem quality score of 0.2 PDF·m^2·y implies the loss of 20% of species on 1 m^2 of earth surface during one year” [32].
- “MJ measures the amount of energy extracted or needed to extract the resource” [32].

At normalized end-point level:

- ““points” are equal to “pers·y”. A “point” represents the average impact in a specific category caused by a person during one year in Europe. In a first approximation, for human health, it also represents the average impact on a person during one year (i.e., an impact of three points in ecosystem quality represents the average annual impact of three Europeans. This last interpretation is also valid for climate change and resources.) It is calculated as the total yearly damage score due to emissions and extractions in Europe divided by the total European population” [32].

2.3.2.1. Midpoint Categories

In this chapter midpoint categories are explained in detail.

Human Toxicity (carcinogenic and non-carcinogenic effects)

“This midpoint category presents “effects on human health except for respiratory effects caused by inorganics, ionizing radiation effects, ozone layer depletion effects and photochemical oxidation effects” in order to avoid duplication since mentioned effects are considered separately because they are evaluated with different approaches” [32].

“CFs for human toxicity are named as “human toxicity potentials” at midpoint level while they are called “human damage factors” at end-point level. A determined chemical emitted in the environment (given in mass) is used for association of cumulative toxicological risk and potential impacts in order to provide estimates. IMPACT2002+ models risks and impacts for each emission of several chemicals through fate and multi-pathway exposure and effects analysis. Human toxicity through agricultural soil is a modified version of emission into soil. CFs are denoted as DALY/kg for end-point level while midpoint level CFs are denoted as kg chloroethylene into air. Emissions considered for this category can be introduced to the environment can be done only through air, water and soil and agricultural soils while no CFs are yet available for ocean, stratospheric emissions and underground water” [32].

Respiratory effects (caused by inorganics)

“In this category CFs are given for air emissions. End-point level CFs are represented in DALY/kg while midpoint CFs are represented as $PM_{2.5}$ into air_{-eq}/kg. $PM_{2.5}$ is considered since it is the portion that causes carcinogenic effects for being the particles that are able to enter the lung. If there is only data regarding PM_{10} correction factor of 0.6 is used to convert the value to $PM_{2.5}$. This is basically due to the fact that particles below 10 μm cover the portion of 2.5 μm.

Respiratory inorganics cover CO, PM_{10} and $PM_{2.5}$ and secondary PM coming from SO_2, NO_x and NH_3” [32].

Ionizing radiation

"CFs given for this category are due to emissions given to air and water. End-point level CFs are represented as DALY/Bq while midpoint level CFs are represented as Bq Carbon 14 into air$_{-eq}$/Bq. Here, reference substance is Carbon-14 into air" [32].

Ozone layer depletion

"For the impact category ozone layer depletion, CFs are given for emissions to air. Midpoint CFs are represented in kg CFC-11 into air$_{-eq}$/kg while end-point CFs are represented in DALY/kg" [32].

Photochemical Oxidation

For the impact category photochemical oxidation, which is given for only emissions into air, there are two types of impacts:

Impact on human health

Impacts caused by photochemical oxidation on human health are also named as respiratory effects from organics. End-point CFs are DALY/kg while midpoint CFs are represented in kg Ethylene air$_{-eq}$/kg.

Impact on ecosystem quality

Photochemical oxidation is known to reduce growth of plants. There are not studies explaining photochemical oxidation's damage on ecosystem quality [32].

Aquatic Ecotoxicity

"CFs for this category are given for emissions into air, water and soil. They quantify the effects on surface water especially streams and lakes. There are not any CFs calculated for groundwater, oceans and stratosphere. End-point CFs are given as PDF.m^2.y/kg, while midpoint CFs are given in kg Triethylene glycol into water$_{-eq}$/

kg. In order to give an example, a new CF is introduced considering C10 and C50 (except for benzene and PAH). Midpoint CF is 0.013 kg Triethylene glycol into $water_{-eq}$/ kg and end-point CF is 6.53 E-7 $PDF.m^2.y/kg$” [32].

Terrestrial Ecotoxicity

“CFs for this category are given for emissions into air, water and soil. End-point CFs are given as $PDF.m^2.y/kg$ while midpoint CFs are given in kg Triethylene glycol into $soil_{eq}$/ kg. Difference between calculation of this category with aquatic ecotoxicity is the only difference is toxic effects are assumed to through aqueous phase in soil” [32].

Aquatic Acidification

“The CFs are determined for air, water and soil. End-point CFs are determined as $PDF.m^2.y/kg$ while midpoint CFs are given in kg SO_2 into air_{-eq}/kg. End-point CFs are calculated by multiplying midpoint CFs by 8.82E-3 $PDF.m^2.y$/ kg SO_2 into air_{-eq}” [32].

Aquatic Eutrophication

“For this category, CFs are given for emissions into air, water and soil. Midpoint CFs are given as kg PO_4^{3-} into $water_{-eq}$/kg while end-point CFs are calculated by multiplying midpoint CFs by 11.4 $PDF.m^2.y$/ kg PO_4^{3-} into $water_{-eq}$. And end-point CFs are expressed as $PDF.m^2.y$/ kg. There exists three different versions of CFs: P-limited, N-limited and undefined. IMPACT 2002+ applies P-limited version” [32].

Terrestrial Acidification and Nutrification

“For this category, CFs are only given for emissions into air. Midpoint CFs are given in kg SO_{2-eq} into air/kg while end-point CFs are given in $PDF.m^2.y$/ kg” [32].

Land Occupation

"For this category, end-point CFs are given as PDF.m^2.y/ m^2.y and midpoint CFs are given as m^2 organic arable $land_{-eq}$ .y/ m^2.y. Humbert et al. [31] states that end-point factors are determined on basis of observations of the number of plant species per area type" [32].

Water Turbined

"This category considers water used for electricity generation by turbines in hydropower dams, and is expressed in m^3 of water. Water utilized for turbine water has impacts for example on ecosystems quality, biodiversity or human health; these impacts depend on location and type of dam" [32].

Global Warming

"Global warming category CFs are for only air emissions. Both midpoint and end-point category for impact from global warming is expresses in kg CO_{2-eq} into air/ kg. There are several CFs used for this category adapted from IPPC list by considering global warming potentials for a 100-year time horizon:

- CO_2 in air = 0 kg CO_{2-eq} / kg
- CO_2 fossil = 1 kg CO_{2-eq} / kg
- CO_2 land transformation = 1 kg CO_{2-eq} / kg
- CO_2 biogenic = 0 kg CO_{2-eq} / kg
- CO fossil = 1.9 kg CO_{2-eq} / kg
- CO biogenic = 0 kg CO_{2-eq} / kg
- CH_4 fossil = 27.75 kg CO_{2-eq} / kg effect of CO_2 from methane degradation is included
- CH_4 biogenic = 25 kg CO_{2-eq} / kg

Biogenic CO_2, CH_4 and CO are explained as:

- Closed biologic cycles are considered mass balanced over a time that is smaller than human life. Therefore both raw CO_2 and biogenic CO_2 have a CF of 0.
- CO_2 from land transformation is not replaced by an equivalent amount of carbon in forest or soil over the same land since it is assumed to result from deforestation or of net reduction in the carbon content of agricultural soils because of oxidation. It is therefore looked at as a fossil emission and therefore has a CF of 1.
- If an amount of CO_2 is considered to be emitted from forest or soil as transformation; and at the same time this CO_2 is considered as an uptake somewhere else in the same inventory, it is classified as biogenic and its CF is 0.
- CH_4, fossil has a CF of 27.75 since global warming potential for 100-years includes the effects of CO_2 that will be created when CH_4 degrades to yield CO_2.
- CH_4, biogenic has a CF of 25. This score is due to global warming potential of CH_4 before it becomes biogenic CO_2 that has a global warming potential of 0; 1 kg of CH_4 results in 2.75 kg of CO_2 once degraded, this value is included in 27.75 kg $CO_{2\text{-}eq}$/kg CH_4, 2.75 kg $CO_{2\text{-}eq}$/kg CH_4 is coming from the CO_2 that will be produced after degradation of CH4, so it means only 25 kg $CO_{2\text{-}eq}$/kg CH_4 is coming from the CH_4 itself before it degrades into CO_2" [32].

Non-renewable Energy

"CFs for non-renewable energy consumption are calculated taking total primary energy extraction. End-point CFs are given in MJ total primary non-renewable energy/unit extracted (can be mass or volume, kg or m^3). Midpoint CFs are expressed in MJ as well" [32].

Mineral Extraction

“For this category, end-point CFs are given as MJ surplus energy/ kg extracted while midpoint CFs are given as MJ. Midpoint CFs can be expressed in kg of iron in ore/ kg extracted but reference substance is not used too commonly” [32].

Water Consumption

“Water consumption is used in the midpoint profile, and its CFs are expressed in m^3. End-point level is not calculated due to incapacity of current softwares, since water consumption and evaporation of water from dams can also be a part of the water withdrawal inventory indicator” [32].

2.3.2.2. End-point Categories

Human Health

This end-point category takes carcinogens, non-carcinogens, respiratory organics, respiratory inorganics, ionizing radiation and ozone layer depletion into consideration. This endpoint category is expressed in DALY: which characterizes the “disease severity, accounting for both mortality (Years of Life Lost due to premature death) and morbidity” [32].

Ecosystem Quality

“This end-point category takes aquatic ecotoxicity, terrestrial ecotoxicity, terrestrial acidification/nutri, land occupation, aquatic acidification, and aquatic eutrophication into consideration. This endpoint category is expressed in PDF* m^2* yr” [32].

Climate Change

“This end-point category considers global warming. It is expressed in kg $CO_{2\ eq}$. This category is dominated by emissions of CO_2” [32].

Resources

“This end-point category covers non-renewable energy and mineral extraction. Unit is MJ. This means MJ primary on non-renewable energy” [32].

2.3.2.3. Normalisation

Normalisation enables the user to make a judgment of allotment of each impact to the overall damage of the category under consideration. It makes it easier to develop an understanding on results by comparing different categories with the same unit.

Normalisation can be done by dividing the impact by normalisation factors. A factor is expressing the total impact of the specific category divided by all European population. “The total impact of the specific category is the sum of the products between all European emissions, resource consumption and respective damage factors” [32]. The normalized characterization factor is determined by the ratio of the impact per unit of emission divided by the total impact of all substances of the specific category per person per year. The unit of all normalized characterization factors therefore [point/$unit_{emission}$] which is also equal to [person.y/ $unit_{emission}$] can be expressed with respective unit per kg, per Bq etc. In Table 6 normalisation factors for midpoint impact categories are given.

Table 6. Normalisation factors for midpoint categories and units for Western Europe [32]

Midpoint Categories	Normalisation Factor	Unit
Human toxicity(carcinogens)	45.5	kg Chloroethylene into air$_{-eq}$
Human toxicity(non-carcinogens)	173	kg Chloroethylene into air$_{-eq}$
Human toxicity(carcinogens+ non-carcinogens)	219	kg Chloroethylene into air$_{-eq}$
Respiratory (inorganics)	8.80	kg $PM_{2.5}$ into air$_{-eq}$
Ionizing radiations	5.33E+5	Bq Carbon 14 into air$_{-eq}$
Ozone layer Depletion	0.204	kg CFC-11 into air$_{-eq}$
Photochemical Oxidation (Respiratory organics for human health)	12.4	kg Ethylene into c
Water withdrawal	3.65E+5	kg Water withdrawal
Aquatic ecotoxicity	1.36E+6	kg Triethylene glycol into water$_{-eq}$
Terrestrial ecotoxicity	1.2E+6	kg Triethylene glycol into soil$_{eq}$
Terrestrial acidification/nutrification	315	kg SO_2 into air$_{-eq}$
Aquatic acidification	66.2	kg SO_2 into air$_{-eq}$
Aquatic eutrophication	11.8	kg PO_4^{3-} into water$_{-eq}$
Land occupation	3460	m^2 organic arable land$_{-eq}$.y
Water turbined	1.7E+4	m^3 water turbined
Global warming	11600	kg CO_2 into air$_{-eq}$
Non-renewable energy	15200	MJ
Mineral extraction	3320	kg Crude oil$_{eq}$ (860 kg/m^3)
	292	MJ
	5730	kg iron$_{-eq}$ (in ore)

In Table 7, normalisation factors for endpoint impact categories are given.

Table 7. Normalisation factors for endpoint end-point categories [32]

End-Point Category	**Normalisation Factor**	**Unit**
Human Health	0.0071	DALY/pers/yr
Ecosystem Quality	13700	PDF.m^2.yr/pers/yr
Climate Change	9950	kg CO_2/pers/yr
Resources	152000	MJ/pers/yr

2.3.4. Interpretation

Interpretation is the last step of LCA where the results obtained from LCI and LCIA are evaluated systematically. The result must be coherent with goal and scope step of the LCA, and be understandable, complete and consistent. Significant issues must be identified through completeness sensitivity, and consistency checks.

2.4. ECONOMIC ANALYSIS

In all decision making situations in which LCA is applied, economic consequences of alternative products/processes must also be taken into the account. However, economic aspects are not within the scope of common LCA methodology and therefore trade-offs between the economic and life cycle performance of are to be taken into account.

It is needless to indicate that textile producers will be very much concerned about the costs of evaporative recovery of mercerizing wastewater besides the environmental burdens given to the environment. In this section, an economic analysis of end-point-treatment and evaporative recovery methods is done to develop an understanding regarding the most feasible solution.

Since time value of money changes by time, proportional to discount rate, which indicates the rate that future cash flows are discounted, is used for converting cash flows to present values [38]. Discount rate is taken from Central Bank of Turkish Republic, and it is 5.5.

In this thesis work, initial, operational and maintenance costs are calculated for end-of-pipe treatment and evaporative recovery options for 20-year period.

"Net present value method, a method for calculating time value of money, is used for determining present value of gain or loss of an investment.

When an investment is done, for example $1, in a government bond paying i% interest per year, money will be $1+i next year. After t years, it will be $1+(1+i)^t. After t years investment will be equivalent to $1/(1+i)^t So, net present value is an estimate of present values of future costs and benefits" [40]. Net present value is calculated as given in equation (1).

$$NPV = \frac{[B(t)-C(t)]}{(1+i)^t} \quad (1)$$

where;

C(t): Costs during period t

B(t): Benefits during period t

i: Discount rate

B(t) – C(t): net benefit

After t years NPV will be calculated as determined in equation (2):

$$\mathrm{NPV} = \sum_{t=0}^{t} \mathrm{B(t)} - \mathrm{C(t)}/(1+i)^t \quad (2)$$

If NPV < 0 the investment is not profitable it will be a financial burden if realized; some beneficial adjustments are neeed, while NPV>0 the project is profitable, it can be further considered.

CHAPTER 3

METHODOLOGY

At the background chapter, general idea of the processes of textile industry is given, especially mercerization by considering the process as a system and illustrates inputs and outputs to this system: raw material, energy consumption, emissions to air, soil and water. Later, by focusing on the emissions and the most common treatment method, namely evaporation, is examined through life cycle assessment tool, SimaPro. Evaporation is evaluated in three different scenarios based on fuels used for steam production (heavy fuel oil, light fuel oil and natural gas). Additionally, to reveal the advantages of evaporation; it is compared to previously employed end-of-pipe treatment method, namely neutralization by H_2SO_4 and activated sludge treatment. Thus, whether replacing end-of-pipe treatment system with evaporation is advantageous in terms of environmental impacts or not will be understood.

In the proceeding sections, field studies conducted, data gathered and LCA approach are presented.

During evaluation of gathered data, SimaPro software version 7.2 is used. It can be used for various analyses such as sustainability reporting, product design, carbon and water foot printing, life cycle assessment. The libraries used are: Ecoinvent (Swiss Centre for Life Cycle Inventories), ELCD (European Life Cycle Database), Industry Data 2.0, LCA Food DK, Methods, USLCI (U.S. Life Cycle Inventory). IMPACT 2002+ version 2.06 is used as method. SimaPro has sub-categories for processes: processes, energy, transport, processing, use, waste scenario, and waste treatment. And sub-categories for product stages: assembly, life cycle, disposal scenario, disassembly and reuse. How these sub categories are used is explained in following sections.

3.1. Field Studies

In context of this thesis study, two different textile factories were visited in Kayseri (Study Plant 1) and Denizli (Study Plant 2). The Study Plant 1 produces denim fabric while the Study Plant 2 produces fabrics, mostly for home textiles. The Study Plant 1 was visited for observatory purposes while the Plant 2 was the one that local inventory data was gathered. The photos in Figure 9 and Figure 10 are taken during site visits.

During these visits, the mercerization processes applied in both of the study plants were observed closely in order to have a clear understanding of the process. In the Study Plant 2, evaporative recovery system was examined thoroughly, and the input-output data to be used as inventory data in LCA analysis of evaporative recovery system was collected. In the Study Plant 1, the current practice regarding mercerization wastewater in other words weak lye was combined treatment with the other wastewater streams.

Figure 9. Mercerization machine in the Study Plant 1 in Kayseri

Figure 10. Evaporator in the Study Plant 2 in Denizli

3.2. Life Cycle Assessment Approach

3.2.1. Goal and Scope Definition

In context of goal and scope definition, goal of the study is set in specific boundaries. Purpose of this thesis work is to determine environmental impacts due to treatment of mercerization wastewater by the evaporative recovery method, in order to recover caustic. And determine environmental impacts caused by the baseline scenario i.e. end-of-pipe treatment of mercerization wastewater. So, the question that should be asked is: "Which mercerization waste handling method is better for the environment, and economically feasible?"

After setting the goal, boundaries should be determined next. "System" under consideration will be reviewed in terms of inputs and outputs. In this thesis work, the boundaries are set as "cradle to grave". In Figure 11 and Figure 12, system under consideration is described.

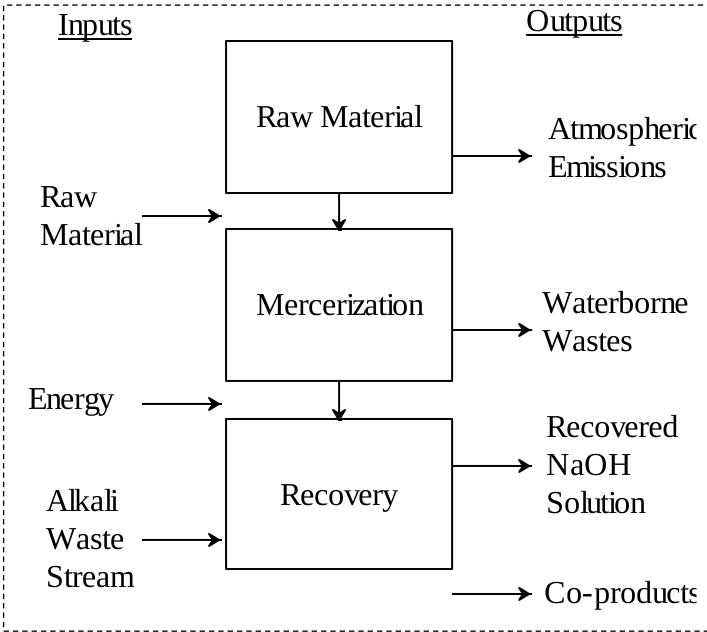

Figure 11. System under consideration for evaporative recovery

Raw material obtainment is one of the causes of atmospheric emissions; water, caustic solution, H_2SO_4, electricity and steam are used for mercerization process. Waterborne waste is produced after mercerization, which is diluted caustic solution, also called as weak lye. For recovery of weak lye, steam, electricity and H_2SO_4 are used. After recovery of caustic solution, some co-products are produced: distilled water and heat.

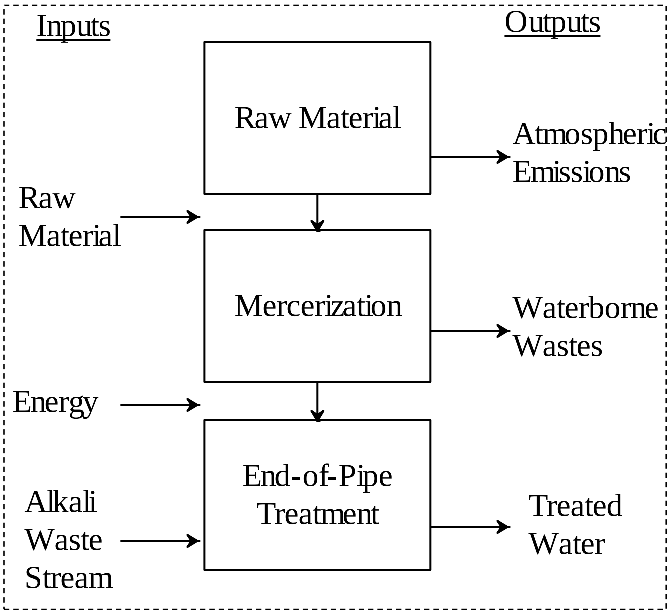

Figure 12. System under consideration for end-of-pipe treatment

In both of the study plants, end-of-pipe treatment receives weak lye from mercerization mixed with other streams from different processes. The treatment applied involves neutralization as preliminary treatment and then conventional secondary treatment involving activated sludge process. The treated wastewater is discharged to a receiving body.

Later on, functional unit is determined to make better comparisons based on an equivalent unit. After introducing mercerization to SimaPro, evaporation process is introduced. During this step functional unit is determined as "per kg wastewater" which is highly alkaline and sent to evaporation for recovery and wastewater treatment plant for treatment.

SimaPro has data quality indicators (DQI) in order to ensure data are of quality; time is selected as 2010 and after, geography is selected as Asia, Middle East, type is assumed as best available technology, representativeness of data is average from a specific process, system boundaries are determined in two sub-categories; cut-off rules are set as less than 5% (environmental relevance), and system boundaries are set as second order since material and energy flow are included. Screenshots of SimaPro regarding DQI's are given in APPENDIX A.

3.2.2. Inventory Analysis

The inventory data to be used in the study was collected from various sources. As indicated above, the main data source was the Study Plant 2. During this step, ultimate attention is paid in order to present precise, complete, accurate, representative, consistent and reproducible data [27]. Data obtained from the Study Plant 2 consists of:

- Meter readings for mercerization machine for steam, electricity and water consumption
- Input-output data for evaporative recovery process that uses natural gas for steam production, this data set included information presented in Table 9

Input and output information of product, process or unit is required to be identified in SimaPro, if it does not already exist in the databases of SimaPro. Mercerization process, which does not exist in any database of SimaPro, is identified with its all inputs and outputs. Later, treatment methods of wastewater originating from mercerization process are described in SimaPro. Firstly, input and output information regarding evaporation method are described. During this step, three different scenarios are identified. Scenarios are based on fuels utilized during steam production for use in evaporation process. These fuels are: heavy fuel oil, light fuel oil and natural gas. And finally, neutralization and end-of-pipe treatment are defined as optional wastewater treatment method, for comparison.

During definition of products, processes and units; some of the materials/processes which already exist in SimaPro's databases are chosen; the rest of the data are manually introduced to SimaPro.

Weak lye (7.3% caustic solution) is introduced to SimaPro under materials category (which is a sub-category of processes); mercerization is introduced under processing, evaporation scenarios and neutralization are introduced under waste treatment. Later, under waste scenario category neutralization is combined with activated sludge treatment process, evaporation scenarios are also defined as waste scenario. All of these are made by defining inputs and outputs of the process and/or waste treatment method.

In order to be able to compare waste scenarios, product stages (assembly and life cycle) are selected among pre-defined processes.

Comparison of treatment methods are done by following the path: In life cycle sub-category, assembly and waste scenario are chosen. Assembly is mercerization process and waste scenario is chosen among three evaporation scenarios and end-of-pipe treatment. After establishing life cycles, comparison is done by clicking to compare button and choose two or more life cycles.

Evaluation process will be explained in detail, in the following topics.

In the following sections inputs-outputs, amount, source of data and explanations regarding inventories of mercerization, evaporation and end-of-pipe treatment are given.

3.2.2.1. Inventory of Mercerization Process

Recalling from Chapter 2, a typical mercerization machine consists of four parts, in impregnation zone wet application is done, in reaction zone 47 ºBé caustic solution is applied to the fabric, in stabilization zone tension is applied to prevent shrinking of the fabric and concentration of caustic solution is decreased, in washing and neutralization zone fabric is washed several times, neutralized by washing H_2SO_4 solution. The machine uses electricity and steam. Steam is required to do hot mercerization. In SimaPro, mercerization is defined manually under sub-category processes. Inventory data for mercerization process was collected from study Plant 2 is presented in Table 8.

Table 8. Inventory of Mercerization Process

Inputs	**Amount Per kg of WW**	**Data Source**	**Explanation as in SimaPro**
Water, process, unspecified natural origin/m3	1.72 L	Meter reading	Raw material
Sodium hydroxide, 50% in H2O, diaphragm cell, at plant/RER U	161 g	Input- output data	"Included processes: Besides the electrolysis process in a diaphragm cell, the following process steps are included into this process: brine production, brine purification, brine resaturation as well as the final handling of the electrolysis products, without the chlorine liquifaction! Remark: The multioutput-process "chlor-alkali electrolysis, diaphragm cell" delivers the co-products "chlorine, gaseous, diaphragm cell, at plant", "sodium hydroxide, 50% in water, diaphragm cell, at plant" and "hydrogen, liquid, diaphragm cell, at plant". The allocation is done according to the masses of the different products - i.e. 46.4% chlorine - 52.3% sodium hydroxide and 1.3% hydrogen" [30]

Table 8. (Cont'd)

H2SO4 ETH S	51.5 g	Input- output data	"Sulphurdioxide gas is oxidized to SO3 using a catalyst. The SO3 is absorbed in concentrated H2SO4, by adding water the SO3 is converted into H2SO4. Data based on a 1991 study. The sulphur used can originate from elementary sulphur, pyrite and other sources such as secondary sulphur. Assumed is that elementary sulphur from Poland is used (800 km transport by train). No capital goods included." [30]
On-site steam average E	0.45	Meter reading	"Nearly all chemical processes need steam. Normally this is generated on site, but it may also be purchased from a nearby generator. Many plants co-generate steam and electricity. Fuels used for steam production vary widely ranging from low grade lignite to natural gas, hydrogen, hydro power or occasionally waste products from the production process itself. If on site steam production is used in a process and the data are known, site specific data are used. This average data set is only used if no data on site steam production is available." [30]
Electricity, production mix/TR2013	0.0075	Meter reading	Electricity production data of Turkey; manually identified in SimaPro. Further details are given in methodology chapter.
Outputs (Waste and emissions to treatment)	**Amount**		**Explanation**
Wastewater treatment, alkali wastewater treatment by evaporation	1 kg		Wastewater sent to evaporator

3.2.2.2. Inventory of Evaporation Process

Weak lye (7.3% caustic solution) is obtained from washing segment of mercerization machine. The wastewater is screened to eliminate particles and it is passed from the evaporator, where it exchanges heat with steam without contacting. Weak lye becomes strong lye (30% caustic solution) after passing from four stages of evaporator. At the end, another product is obtained, namely distilled water. Strong lye is cooled by the aid of cooling water, which becomes hot water at the end. Also strong lye is purified in purification tank by the aid of hydrogen peroxide. The Study Plant 2 aims zero liquid discharge from evaporator. For this purpose, they are using all the effluents from evaporator back in mercerization process. Condensate, hot water and distilled water are utilized in rinsing and washing segments of mercerization machine. Heat from hot water is also recovered in mercerization process since the Study Plant 2 is employing hot mercerization. Inventory of evaporation process is given in Table 9.

Table 9. Inventory of Evaporation Process

Inputs	**Amount**	**Data Source**	**Explanation**
Water, cooling, unspecified natural origin/kg	10.9 kg	Input-output data	Raw material
Hydrogen peroxide, 50% in H2O, at plant/RER U	0.7 g	Input-output data	"Included processes: This module contains material and energy input, production of waste and emissions for the production of hydrogen peroxide by the anthrachinone process. Transport and infrastructure have been estimated. The input of 215 g air is not reported in the data according to the methodology of the study." [30]
Electricity, production mix/TR2013	0.43 kwh	Input-output data	

Table 9. (Cont'd)

Process steam from natural gas, heat plant, consumption mix, at plant, MJ EU-27 S	2.03 MJ	Input-output data	"Process steam (MJ) at heat plant for final consumers.; Technology description including background system: The EU-27 specific Process steam from natural gas mix 'Process steam from natural gas EU-27 Mix'. Each country provides a certain amount of steam to the mix. The process steam is produced in natural gas specific heat plants. Each country specific fuel supply (share of resources used, by import and / or domestic supply) including the country specific energy carrier properties (e.g. element and energy contents) are accounted for. Furthermore country specific technology standards of heat plants regarding firing technology, flue-gas desulphurisation, NOx removal and dedusting are considered. The data set considers the whole supply chain of the fuels from exploration over extraction and preparation to transport of fuels to the heat plants. The background system is addressed as follows: Transports: All relevant and known transport processes used are included. Overseas transports including rail and truck transport to and from major ports for imported bulk resources are included. Furthermore all relevant and known pipeline and / or tanker transport of gases and oil imports are included. Energy carriers: Coal, crude oil, natural gas and uranium are modelled according to the specific import situation. Refinery products: Diesel, gasoline, technical gases, fuel oils, basic oils and residues such as bitumen are modelled via a country-specific, refinery parameterized model. The refinery model represents the current national standard in refinery techniques (e.g. emission level, internal energy consumption,...) as well as the individual country-specific product output spectrum, which can be quite different from country to country. Hence the refinery products used show the individual country-specific use of resources. The supply of crude oil is modelled, again, according to the country-specific crude oil situation with the respective properties of the resources" [30].

Table 9. (Cont'd)

Process steam from light fuel oil, heat plant, consumption mix, at plant, MJ EU-27 S			"Technical purpose of product or process: Process steam (MJ) at heat plant for final consumers.; Technology description including background system: The EU-27 specific Process steam from light fuel oil mix is shown in the pie chart 'Process steam from fuel oil EU-27 Mix'. Each country provides a certain amount of steam to the mix. The process steam is produced in natural gas specific heat plants. Each country specific fuel supply (share of resources used, by import and / or domestic supply) including the country specific energy carrier properties (e.g. element and energy contents) are accounted for. Furthermore country specific technology standards of heat plants regarding firing technology, flue-gas desulphurisation, NOx removal and dedusting are considered. The data set considers the whole supply chain of the fuels from exploration over extraction and preparation to transport of fuels to the heat plants. The background system is addressed as follows: Transports: All relevant and known transport processes used are included. Overseas transports including rail and truck transport to and from major ports for imported bulk resources are included. Furthermore all relevant and known pipeline and / or tanker transport of gases and oil imports are included. Energy carriers: Coal, crude oil, natural gas and uranium are modelled according to the specific import situation. Refinery products: Diesel, gasoline, technical gases, fuel oils, basic oils and residues such as bitumen are modelled via a country-specific, refinery parameterized model. The refinery model represents the current national standard in refinery techniques (e.g. emission level, internal energy consumption,..) as well as the individual country-specific product output spectrum, which can be quite different from country to country. Hence the refinery products used show the individual country-specific use of resources. The supply of crude oil is modelled, again, according to the country-specific crude oil situation with the respective properties of the resources" [30].

Table 9. (Cont'd)

Process steam from heavy fuel oil, heat plant, consumption mix, at plant, MJ EU-27 S			"Technical purpose of product or process: Process steam (MJ) at heat plant for final consumers.; Technology description including background system: The EU-27 specific Process steam from heavy fuel oil mix is shown in the pie chart 'Steam from Fuel oil EU-27 Mix'. Each country provides a certain amount of steam to the mix. The process steam is produced in natural gas specific heat plants. Each country specific fuel supply (share of resources used, by import and / or domestic supply) including the country specific energy carrier properties (e.g. element and energy contents) are accounted for. Furthermore country specific technology standards of heat plants regarding firing technology, flue-gas desulphurisation, NOx removal and dedusting are considered. The data set considers the whole supply chain of the fuels from exploration over extraction and preparation to transport of fuels to the heat plants. The background system is addressed as follows: Transports: All relevant and known transport processes used are included. Overseas transports including rail and truck transport to and from major ports for imported bulk resources are included. Furthermore all relevant and known pipeline and / or tanker transport of gases and oil imports are included. Energy carriers: Coal, crude oil, natural gas and uranium are modelled according to the specific import situation. Refinery products: Diesel, gasoline, technical gases, fuel oils, basic oils and residues such as bitumen are modelled via a country-specific, refinery parameterized model. The refinery model represents the current national standard in refinery techniques (e.g. emission level, internal energy consumption,...) as well as the individual country-specific product output spectrum, which can be quite different from country to country. Hence the refinery products used show the individual country-specific use of resources. The supply of crude oil is modelled, again, according to the country-specific crude oil situation with the respective properties of the resources" [30].

Table 9. (Cont'd)

Outputs	**Amount**	**Data Source**	**Explanation**
Sodium hydroxide (concentrat ed) E	0.073 kg	Input-output data	
Water, hot water, from evaporation , TR	10.9 kg	Input-output data	Raw material
Water, deionised, at plant/CH U	0.757 kg	Input-output data	"Included processes: Energy for operation, chemicals used for regeneration, transport of chemicals to plant, emissions from regeneration chemicals, infrastructure of plant and replacement of spent exchane resin. Process does not include very small units (cartridges) or very large units with >>100 m3/h (power stations). Other production methods as reverse osmosis electrodialysis or distillation are not covered with this process (only ion exchange). Remark: Large uncertainties exist due to influence of raw water quality and operation mode on regeneration chemical demand and electricity used. Raw water data from Switzerland (drinking water of Zurich and Basel). For electricity demand swiss supply mix used. Technology: Process includes a strong cation exchanger a degasser and a strong anion exchanger unit is operated with counterflow regeneration. Obtained water quality about 1 uS/cm for the conductivity and a silica content (as SiO2) of 5-25 ug/l. As water resource tap water from a public supply with a total hardnes of 1.71 mol/m3 (range 0.7 - 3.2) was assumed. No lime decarbonation as pretreatment is used" [30].
Heat, unspecific, in chemical plant/RER U	1.79 MJ	Input-output data	"Included processes: Includes the heat production needed for the production of 1 MJ (=0.3636 kg) steam from cold water. Does not include the water input because steam is often used in closed systems" [30].

3.2.2.3. Inventory of end-of-pipe treatment

Additionally, end-of-pipe treatment of mercerization wastewater is also evaluated. In this method, firstly wastewater is neutralized by using H_2SO_4, and wastewater is sent to treatment plant, treated by activated sludge process. The processes taking place in waste water treatment plant are already defined in SimaPro. Simply by combining secondary treatment of the weak lye by activated sludge process with neutralization (by H_2SO_4) under the "waste scenario sub-category" of SimaPro, this option is introduced to SimaPro.

All inputs and outputs of end-of-pipe treatment are already introduced to SimaPro. In addition to that, for neutralization of alkali effluent of mercerization the chemical reaction is considered:

1g NaOH + 1.225g $H_2SO_4 \rightarrow$ 1.775 g Na_2SO_4 + 0.45 g H_2O

Data regarding H_2SO_4 is obtained from Study Plant 1; the process is introduced to SimaPro manually. Information regarding end-of-pipe treatment is given in Table 10.

Table 10. Information regarding end-of-pipe treatment

Inputs	**Amount (per kg of wastewater)**	**Explanation as in SimaPro**
Neutralization	1 kg	Inputs are H_2SO_4 and weak lye. For 1g of NaOH, 1.25 g H_2SO_4 is required.

Table 10. (Cont'd)

Wastewater untreated, slightly organic contaminated, EU-27 S	1 kg	"The data set represents an end-of-life inventory. Treatment for waste water (slightly organic and anorganic contaminated) from industrial processes.; This data set covers all relevant inputs and outputs from the treatment of incoming waste water from industrial processes. It contains mechanical, biological and chemical treatment steps for the waste water (including precipitation and neutralisation), and treatment steps for the sludge (thickening, dewatering, drying, conditioning and incineration). The outflow goes directly to the receiving water (natural surface water)." [30]

Note regarding some abbreviations used in Tables 8, 9 and 10:

- ETH: Data from Swiss Federal Institute of Technology Zurich
- CH: Swiss Data
- RER: indication of geographic boundary: Europe
- U: unit process
- S: system process
- EU-27: Average from 27 European Countries
- E: Average

"Water, hot water, from evaporation, TR" and "Electricity, production mix/TR2013" are introduced to SimaPro manually since they did not already exist in SimaPro.

During introduction of electricity production of Turkey, a study is considered [33], that is giving distribution of energy sources for electricity production of Turkey as in Table 11.

Table 11. Electricity production and source utilization percentages in Turkey [33]

Source	**Electricity production percentage (%)**
Hydraulic	24.1
Natural gas	43.2
Lignite	14.4
Imported coal	12.1
Biogas	0.3
Wind	2.4
Fuel oil	2
Coal	0.7
Geothermal	0.4
Asphaltite	0.4

Several assumptions are made to fit these data in SimaPro, energy sources with percentages smaller than 10%, given in Table 11 are neglected and new percentages are assumed to be as stated in Table 12.

Table 12. Assumed values for electricity production and source utilization percentages in Turkey

Source	**Electricity production percentage (%)**
Hydraulic	25
Natural gas	45
Lignite	16
Imported coal	14

During identification of electricity production of Turkey to SimaPro, some assumptions are made:

- During introduction of country specific data, similarities in terms of geography were considered. For example, lignite from Turkey was assumed to be similar to lignite of Greece, regarding natural gas which is imported from Russia, data belonging to Russia was considered.
- Transportation of fuels is not taken into account since all the fuels are assumed to exist in Turkish borders.
- If there is no information, unspecified origin was chosen from SimaPro.

During identification of evaporation the following assumption is done:

- Distilled water production is a result of evaporation. Deionized water is assumed to have same characteristics with distilled water.

Assumption regarding input and output data:

- Data obtained from Study Plant 2 represent average values of Turkey.

3.2.3. Life Cycle Impact Assessment

Following inventory analysis, life cycle impact assessment is conducted simply by calculating on SimaPro. Steps of impact assessment are: characterization, end-point categories, normalisation, weighting, and single score. During characterization pre-defined CF's are used to multiply amount of a substance and contribution to the impact is determined. Later, all multiplied values are summed up and corresponding category indicators are represented at the midpoint level. At end-point assessment step, the midpoint level indicators are related to an endpoint level indicator. Endpoint level indicators are called as end-point categories. Midpoints having effect on ecosystem quality are added and represented with the same unit. Another step is normalisation which helps equalize units of endpoint impact categories and represent them with the same unit. Thus make the comparison easier. An optional step, weighting helps the user to make judgment regarding significance of an impact category. Single score sums up normalisation and weighting score, thus lower the impact to a single score. Comparison is made easy thus decision making is favored.

3.2.4. Interpretation

Interpretation is the last step of LCA. Results are evaluated in this step. Normalized and single score are taken into consideration during evaluation of results. There are two treatment scenarios, first one is solely evaporation and the other scenario is comparing evaporation with combined neutralization and wastewater treatment.

3.3. Economic Analysis

Comparison of end-of-pipe treatment and evaporative recovery is done economically. Net Present Value (NPV) is used in order to do economic analysis, by establishing a formula in excel.

The calculations are done for operation and maintenance; and investment. During operation and maintenance NPV calculations, it is assumed that costs do not change by time. Economic life of the projects is considered as 20 years. Yearly costs are calculated per treatment and evaporation of per m^3 of weak lye. NPV coefficient is calculated by using the formula $1/(1+i)^t$ for each respective year. NPV of each year is found by multiplying cost by corresponding NPV coefficient; later NPV values for 20 years are summed up. The result is converted to €/ton by dividing the sum of NPVs to ton of weak lye processed for 20 years.

Costs regarding the evaporator are obtained from the producer, which the Study Plant 2 purchased the current evaporator in use; costs regarding the end-of-pipe treatment are obtained from the data of a similar wastewater treatment plant that of the Study Plant 2 is operating. Since the wastewater treatment plant does not only treat wastewater coming from mercerization unit; the amount of water coming from mercerization unit is assumed to be total amount that wastewater treatment plant receives. For that reason, costs are proportioned accordingly.

Information regarding treatment units is given as follows:

Information of costs regarding evaporator:

First investment cost: 400.000€

Operation and maintenance cost: 114.9 €/d

Information of costs regarding wastewater treatment plant:

First investment cost: 1.600.000 €

Operation and maintenance cost: 4.800 € (cost of H_2SO_4 is included)

The total amount that wastewater treatment plant receives 9750 m^3/d, while total amount of wastewater discharged from evaporation unit is 1150 m^3/d.

$\frac{9750\ m3/d}{1150\ m3/d}$= 8.47 approximately 8.5

So, the costs of wastewater treatment plant are assumed to be:

First investment cost: 188.235 €

Operation and maintenance cost: 564.7 €/d (cost of H_2SO_4 is included)

The information of calculation results are given in Table 13.

Table 13. Data regarding NPV calculations for first investment and operation & maintenance

	First Investment for Evaporation	**Operation and Maintenance for Evaporation**	**First Investment for End-of-Pipe Treatment**	**Operation and Maintenance for End-of-Pipe Treatment**
Cost	400.000 €	114.9 €/d	188.235 €	564.7 €/d
Yearly Cost	-	41.939 €/d	-	206.118 €/d
NPV	526.063 €	380.048 €	178.846 €	2.585.474 €
€/ton	1	0.7	5	0.3

In addition to costs, some revenues are obtained due to prevention of possible expenses if recovery of materials and heat was not done. The revenues are considered as benefits. Yearly costs are calculated and the same calculations are repeated. At the end revenues are found as €/ton. Detailed information is given in Table 14. The results of the NPV calculations are given in Chapter 4.

Table 14. Data regarding revenues from recovery of NaOH, distilled water and heat

	NaOH	**Distilled Water**	**Heat**
Cost (€)	378.400	80.125	493.830
NPV(€)	4.746.528	1.005.062	6.194.445
€/ton	9.1	1.9	11.9

CHAPTER 4

RESULTS AND DISCUSSION

In this chapter, the results of the life cycle assessment carried out using SimaPro software for the evaporative caustic recovery process are presented and compared to those of the end-of-pipe treatment method that the textile factories conventionally use.

The Study Plant 2 that the inventory data is gathered from, has recently started to apply evaporative recovery. Before the evaporator has been set into operation, the Study Plant 2 was treating weak lye originating from mercerization process in a wastewater treatment plant that receives all wastewater from the Study Plant 2 and employs secondary treatment by the activated sludge process. Therefore, LCA results presented in this chapter are specific to the Study Plant 2 as most of the inventory data used in LCA of evaporative recovery process belongs to this textile plant. However, this does not mean that the LCA results obtained from the study are not generic. It is thought that the results are specific to Turkey but not to the Study Plant 2, as the Plant uses a pre-fabricated evaporative recovery system.

As stated in the previous chapter, environmental impacts are calculated via IMPACT 2002+ method. Normalisation and single score graphs are considered during the evaluation of results.

Mid-point impact categories have different units and this fact makes comparison of impacts impossible. End-point assessment represents end-point impact categories with the same unit; thus enabling comparison of environmental impacts of materials/processes/products. Normalized scores are the same with weighting scores, due to the fact that IMPACT 2002+ has the default value of 1 as the weighting factor. So, consideration of normalized scores is thought to be enough for interpretation. Score of single score step is simply obtained by summing up normalisation scores under the same end-point impact category. Comparison is made based on single score results. Unless otherwise indicated, unit of these scores are Pt (point) where 1 mPt (millipoint) makes 0.001 Pt.

A financial evaluation is also presented in this chapter of the thesis, to analyze profitability for the assessment of the evaporative recovery option's potential return on investment

4.1. Environmental Impacts of Mercerization Process

Mercerization process is done by stretching fabric, and passing it through mercerization machine while applying 47º Bé caustic solution, and steam; the machine uses electricity and H_2SO_4 for neutralization of the fabric. In Figure 14, environmental impacts of mercerization process per impact category are given.

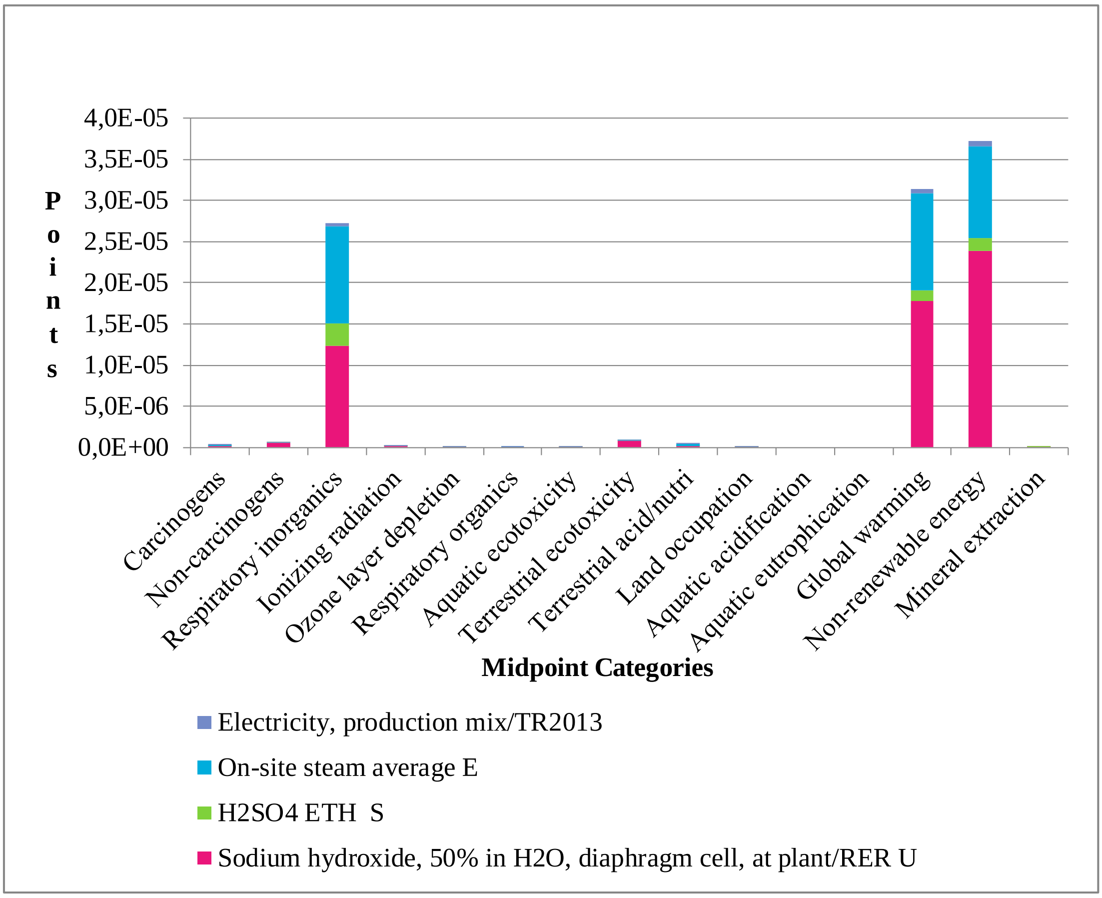

Figure 13. Environmental impacts of mercerization

As seen in **Error! Reference source not found.**, the process of mercerization has the highest impacts on respiratory inorganics, global warming and non-renewable energy mid-point impact categories on the environment. The results indicate that, mainly sodium hydroxide production has the highest impact followed by steam production on-site.

Impacts in respiratory inorganics category are mainly caused by PM_{10} and $PM_{2.5}$ NO_x, SO_2, ammonia. Sodium hydroxide production and electricity production are the processes that emit gasses the most. Respiratory inorganics are mostly emitted due to combustion of fuels during energy production; the need for energy production emerges from NaOH and electricity production.

CO_2, N_2O, CH_4, which are greenhouse gasses, emitted to air from fuel combustion the causes of global warming. The fuel burning processes are mainly due to combustion of various fuels for electricity generation and NaOH production.

Non-renewable energy impacts are due to raw material extraction for energy production. According to the results from SimaPro, mainly coal and natural gas extraction for steam production are the causes behind this midpoint impact category. However in the diagram NaOH production, represented by the pink bars, seems to be having greater impact.

In Table 15, scores of each midpoint category are given.

Table 15. Scores of midpoint impact categories for the mercerization process

Impact category	**Score of Mercerization**
Carcinogens	2.42E-07
Non- carcinogens	5.54E-07
Respiratory inorganics	2.72E-05
Ionizing radiation	1.66E-07
Ozone layer depletion	2.22E-09
Respiratory organics	7.54E-09
Aquatic ecotoxicity	6.7E-08
Terrestrial ecotoxicity	8.78E-07
Terrestrial acid/nutrification	3.96E-07
Land occupation	3.48E-08
Aquatic acidification	0.0E+00
Aquatic eutrophication	0.0E+00
Global warming	3.15E-05
Non-renewable energy	3.72E-05
Mineral extraction	7.11E-10

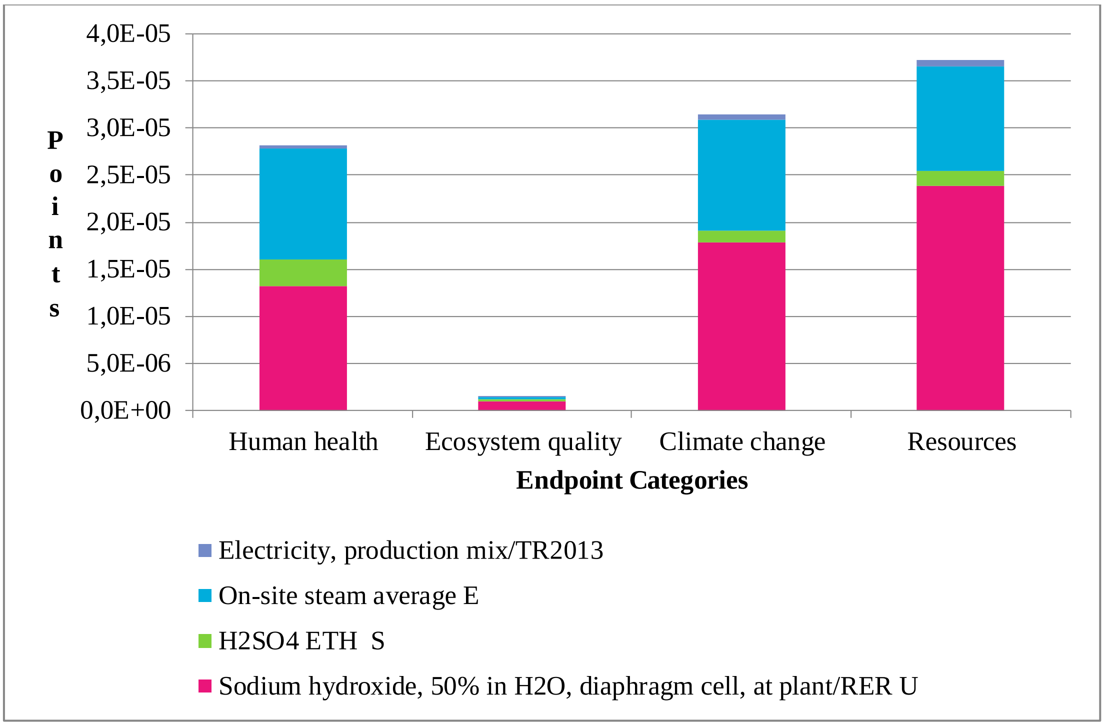

Figure 14. Environmental impacts of mercerization per endpoint impact category

The impacts of mercerization process with respect to end-point impact categories are presented in Figure 15. According to Figure 15, mercerization has the biggest impact on natural resources; the impact is mostly due to sodium hydroxide production. Its second biggest impact is on climate change, again the processes responsible for this impact are sodium hydroxide production and steam generation; and this endpoint category is followed by human health, while it has the minimum impact on the ecosystem quality. Sodium hydroxide production for use in mercerization process has higher scores in each endpoint category. In Table 16, scores are presented for each endpoint category.

Table 16. Scores of mercerization per end-point impact category

Endpoint Category	**Score**
Human Health	2.82E-05
Ecosystem Quality	1.37E-06
Climate Change	3.15E-05
Resources	3.72E-05

4.2. Environmental Impacts or Evaporative Recovery - Scenarios Based on Fuels Utilized for Steam Production

In the evaporative recovery of weak lye, evaporation is done by employing a series of plate heat exchangers; steam is passed through pipes, transferring its heat to weak caustic solution (11 ˚Bé), and separating caustic solution to its components. While passing through heat exchanger, steam and caustic solution do not contact. At the end, steam condenses forming condensate; while caustic solution in converted to two different streams: distillate and strong caustic solution (36 ˚Bé). Strong caustic solution is hot when leaving the evaporator, cooling water is used for decreasing the temperature of strong caustic solution. Cooling water and strong caustic solution do not contact too. Condensate, hot water and distillate are used in the Study Plant 2 as well as strong caustic solution, thus making zero discharge.

During steam production, water is heated and for this purpose combustion is employed SimaPro’s databases presents steam production in industrial facilities with three types of fuels: heavy fuel oil (HFO), light fuel oil (LFO), and natural gas (NG). All the three scenarios are considered and their impacts are compared with that of end-of-pipe treatment. The scenario with less environmental impact is taken into consideration for final comparison with end-of-pipe treatment as the result, the method that Study Plant 2 actually uses for steam production. Electricity is also needed in order to operate pumps.

In Figure 16, comparison of steam scenarios is shown per midpoint impact category.

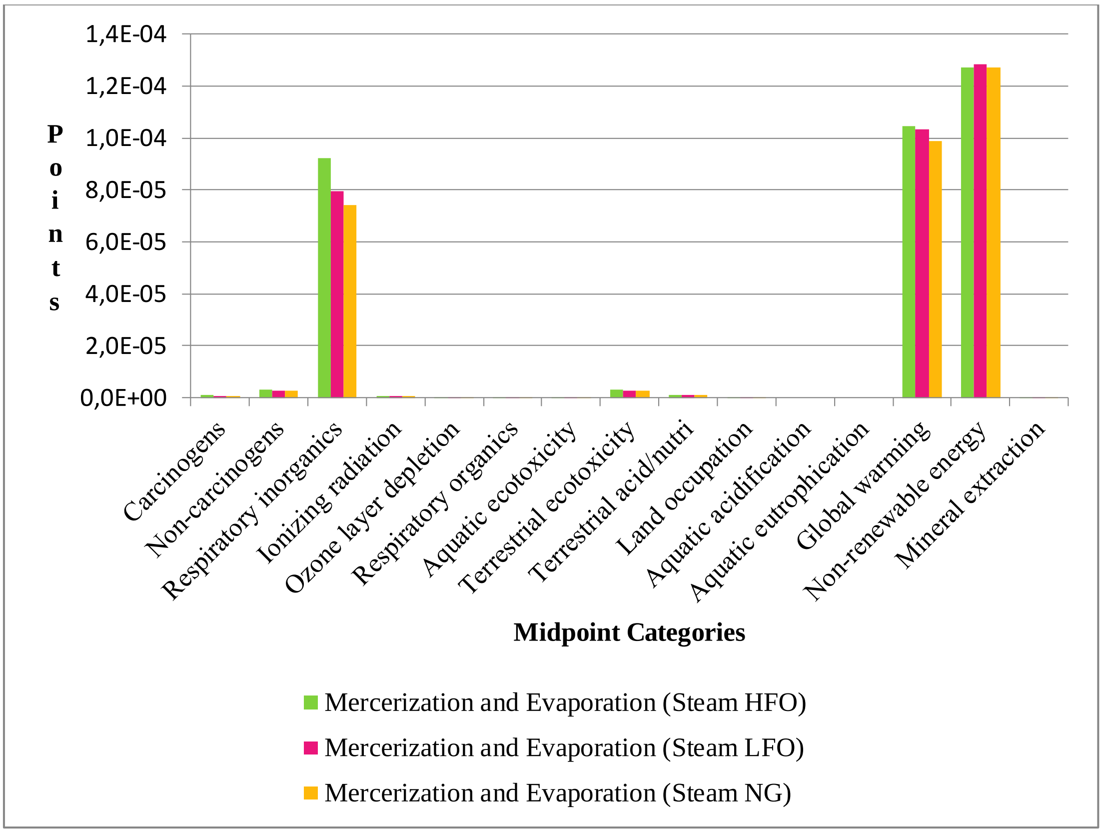

Figure 15. Comparison of steam scenarios

In this section, comparison of evaporative treatment methods based on fuels utilized for steam production will be evaluated. Since evaporative recovery is “zero liquid discharge” method; mainly emissions to air occur. The emissions occur due to energy production for heating the weak lye by steam. The impacts are in respiratory inorganics, global warming and non-renewable energy midpoint categories. In respiratory inorganics and global warming categories, evaporation done with steam which is produced using heavy fuel oil has the greatest impact. For aforementioned categories, second biggest scores belong to evaporation done with steam which is produced using light fuel oil. For non-renewable energy category, evaporation done with steam which is produced using light fuel oil has the greatest impact on the environment. Second bigger scores belong to evaporation done with steam which is produced using heavy fuel oil. For all of the categories, evaporation done with steam which is produced using natural gas have the lowest scores. Evaporation done with steam which is produced using natural gas is the most environmentally friendly option.

Respiratory inorganics are $PM_{2.5}$, SO_2, SO_x, NO_x emitted from processes like burning hard coal, lignite and corresponding fuels for steam production. Emissions to air that cause global warming are CO_2 and CH_4. CO_2 has two types land formation and fossil. The emissions are caused by steam production with corresponding fuels and electricity generation. Resources depleted are crude oil and coal (brown and hard).

In the table 17, scores are presented.

Table 17. Scores of comparison of three steam scenarios

Impact category	**Score of Evaporation (HFO)**	**Score of Evaporation (LFO)**	**Score of Evaporation (NG)**
Carcinogens	9.14E-07	8.65E-07	8.33E-07
Non- carcinogens	3.07E-06	2.8E-06	2.8E-06
Respiratory inorganics	9.21E-05	7.95E-05	7.44E-05
Ionizing radiation	6.26E-07	6.26E-07	6.26E-07
Ozone layer depletion	1.36E-08	1.36E-08	1.36E-08
Respiratory organics	4.2E-08	4.2E-08	4.01E-08
Aquatic ecotoxicity	3.16E-07	3.16E-07	3.16E-07
Terrestrial ecotoxicity	3.03E-06	2.82E-06	2.83E-06
Terrestrial acid/nutrification	1.2E-06	1.11E-06	9.89E-07
Land occupation	1.82E-07	1.82E-07	1.82E-07
Aquatic acidification	0	0	0
Aquatic eutrophication	0	0	0
Global warming	0.0001	0,0001	9.89E-05

Table 17. (Cont'd)

Non-renewable energy	0.0001	0.0001	0.0001
Mineral extraction	3.93E-09	3.83E-09	3.93E-09

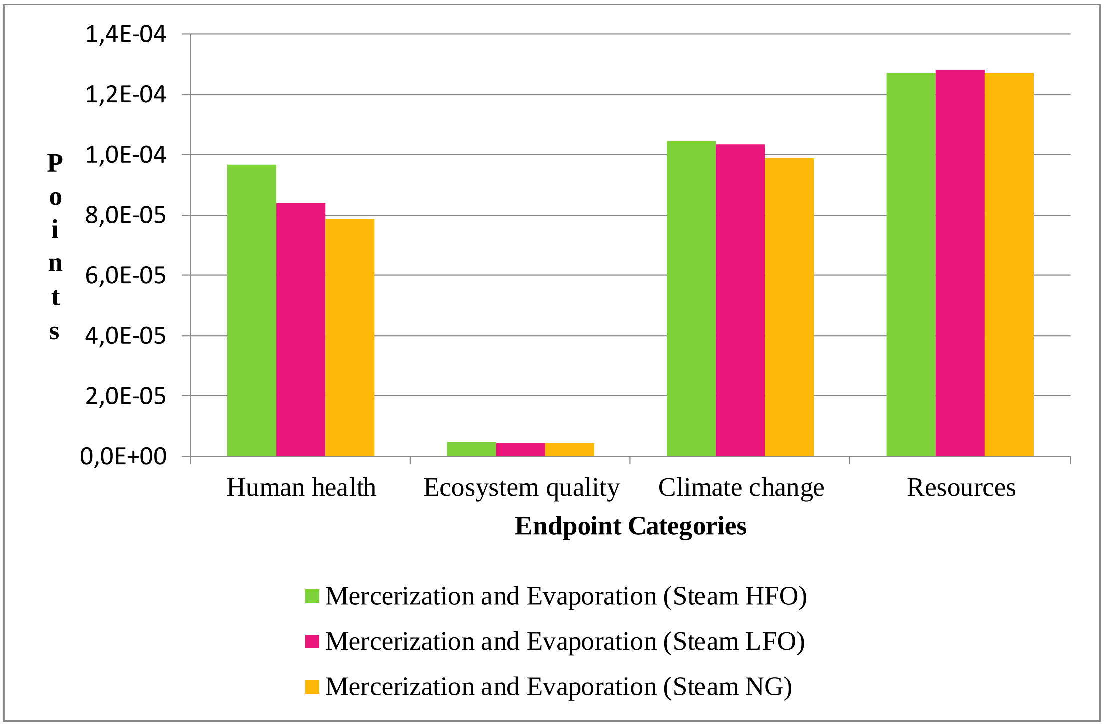

Figure 16. Comparison of steam scenarios

In Figure 17, comparison of steam scenarios is done based on endpoint categories. Since evaporation process requires combustion of fuels, gaseous compounds emitted to air cause problems in human health, contribute to climate change and deplete resources. Utilizing natural gas for steam production for use in evaporation leads fewer problems. For human health and climate change endpoint categories, evaporation done with steam that is produced using heavy fuel oil has the higher points, i.e. more impacts on the environment. For resources endpoint category evaporation done with steam that is produced using light fuel oil has the higher point.

For each endpoint category, evaporation done with steam that is produced using natural gas has the less point, so using natural gas for steam production is a preferable option.

In table 18, scores are given per endpoint impact category.

Table 18. Scores of steam scenarios per endpoint impact category

Endpoint Category	**Score (Steam with HFO)**	**Score (Steam with LFO)**	**Score (Steam with NG)**
Human Health	9.68E-05	8.39E-05	7.87E-05
Ecosystem Quality	4.73E-06	4.42E-06	4.31E-06
Climate Change	0.0001	0.0001	9.89E-05
Resources	0.0001	0.0001	0.0001

4.3. Comparison of End-of-Pipe Treatment with Evaporative Recovery Utilizing Heavy Fuel Oil for Steam Production

In this part, end-of-pipe treatment is compared with evaporative recovery which uses steam utilizing heavy fuel oil (Indicated as HFO in Figure 18.)

Comparison is made based on midpoint impact categories.

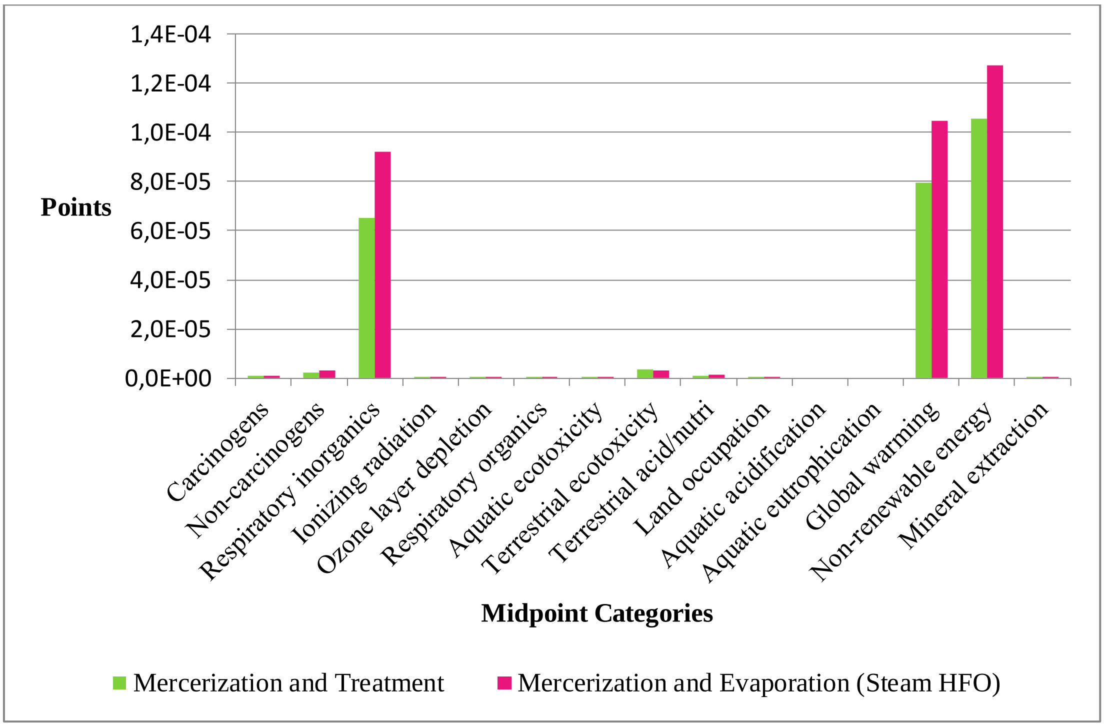

Figure 17. Comparison of end of pipe treatment and evaporation

Both end-of-pipe treatment and evaporation requires energy, from electricity and steam; at the end of energy production processes, gaseous compounds are emitted to air. These emissions result in global warming, produce respiratory inorganics and deplete non-renewable sources.

As seen in Figure 18, for each endpoint category mentioned above, evaporation has higher scores due to use of heavy fuel oil. Since it is the residue of crude oil refining, combustion products are high in NO_x, SO_x, $PM_{2.5}$ and CO_2.

For respiratory inorganics category end-of-pipe treatment emits SO_2, SO_x, $PM_{2.5}$, and NO_x (the substances are given in decreasing order). Emissions are originating from burning natural gas; H_2SO_4 production and burning lignite and hard coal for electricity production.

For global warming category CO_2, fossil and land transformation and CH_4 are mainly emitted from evaporation unit while end of pipe treatment emits CO_2, fossil and CH_4. Processes responsible for such impact are burning heavy fuel oil and steam production; burning lignite and hard coal and production of H_2SO_4.

For non-renewable energy category, crude oil and energy produced by using oil are the substances responsible for environmental impacts originating from evaporation. The processes that cause depletion of these sources are mining and onshore oil production. End-of-pipe treatment utilizes lignite, hard coal and natural gas and the processes that cause this effect is mining activities for fuel obtainment. H2SO4 production for neutralization is another process that use non-renewable energy.

In Table 19, scores are given; the biggest difference is in global warming midpoint category.

Table 19. Scores of end-of-pipe treatment and evaporative recovery

Midpoint Impact Category	**Score (End-of-Pipe Treatment)**	**Score (Evaporation with HFO)**
Carcinogens	9.98E-07	9.14E-07
Non-carcinogens	2.19E-06	3.07E-06
Respiratory inorganics	6.51E-05	9.21E-05
Ionizing radiation	6.35E-07	6.26E-07
Ozone layer depletion	1.02E-08	1.36E-08
Respiratory organics	3.01E-08	4.2E-08
Aquatic ecotoxicity	3.59E-07	3.16E-07
Terrestrial ecotoxicity	3.56E-06	3.03E-06
Terrestrial acid/ nutrification	8.84E-07	1.2E-06
Land occupation	1.86E-07	1.82E-07
Aquatic acidification	0	0
Aquatic eutrophication	0	0

Table 19. (Cont'd)

Global warming	7.95E-05	0.000105
Non-renewable energy	0.000105	0.000127
Mineral extraction	3.98E-09	3.93E-09

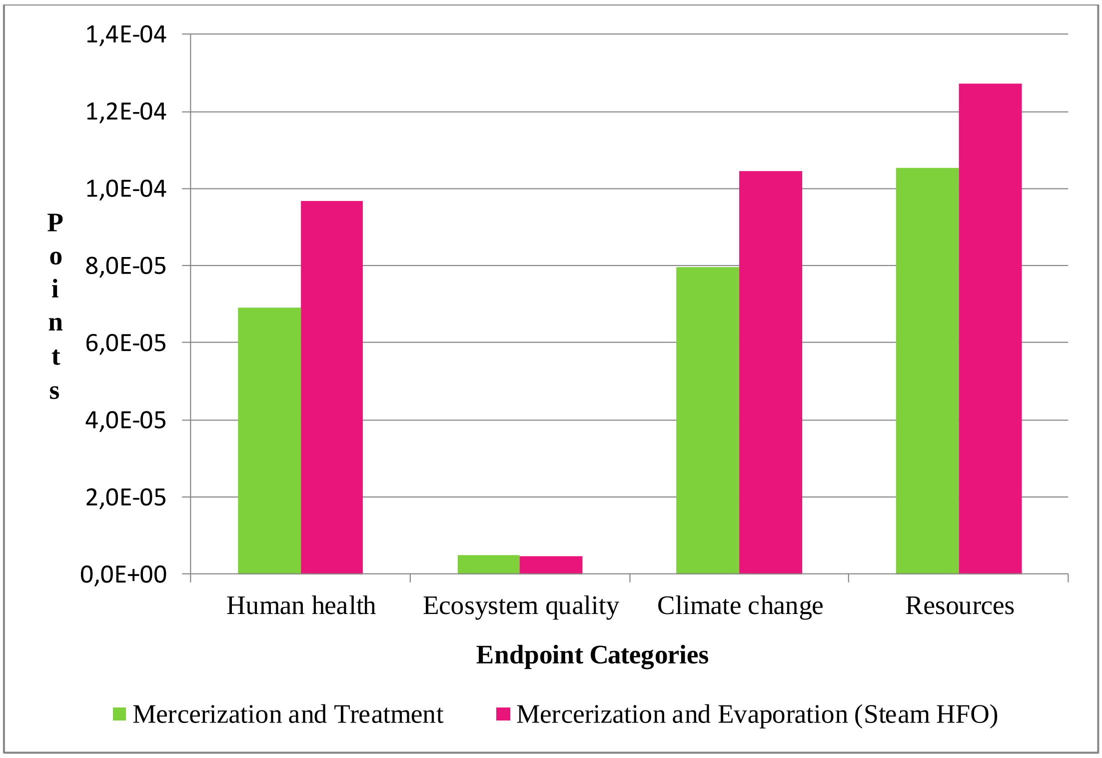

Figure 18. Comparison of end of pipe treatment and evaporation based on endpoint impact categories

In Figure 19, comparison of end-of-pipe treatment and evaporation is shown based on endpoint categories. In human health, climate change and resources categories evaporation has the higher scores. Table 20 shows scores of end-of-pipe treatment and evaporative recovery per endpoint impact category. Resources category has the highest score.

Table 20. Scores of end-of-pipe treatment and evaporative recovery

Endpoint Category	**Score (End-of-pipe treatment)**	**Score (Evaporation)**
Human health	6.9E-05	9.68E-05
Ecosystem quality	4.99E-06	4.73E-06
Climate change	7.95E-05	0.000105
Resources	0.000105	0.000127

4.4. Comparison of End-of-Pipe Treatment with Evaporative Recovery Utilizing Natural Gas for Steam Production

In this part of the thesis work, end-of-pipe treatment is compared with evaporative recovery which uses steam produced with natural gas. Natural gas has the least environmental impact among the three evaporation scenarios. In Figure 20, end-of-pipe treatment and evaporation done by using steam produced with natural gas are compared based on midpoint impact categories.

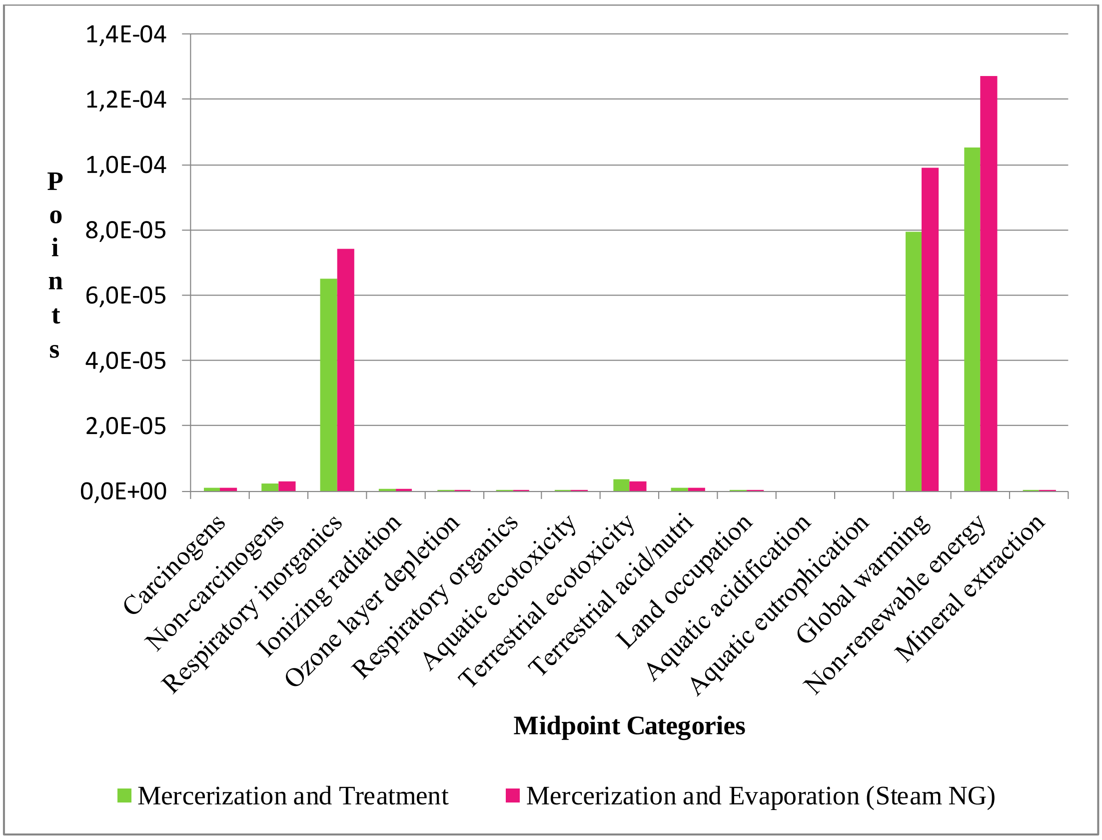

Figure 19. Comparison of end of pipe treatment and evaporation

In this section of the thesis work, the same categories in evaporation using steam which is produced with HFO are seen here too; namely, respiratory inorganics, global warming and non-renewable energy. The emissions are mainly emitted to air. For each midpoint impact category mentioned above, evaporation has greater scores.

For some midpoint categories end-of-pipe treatment has higher scores than evaporation however these scores are negligible compared to that of respiratory inorganics, global warming and non-renewable energy. The categories where end-of-pipe treatment has higher scores (aquatic ecotoxicity and terrestrial ecotoxicity) are related to discharge of treated wastewater.

For respiratory inorganics endpoint category, evaporation emits $PM_{2.5}$, SO_2, SO_x, and NO_x while end-of-pipe treatment emits SO_2, SO_x, $PM_{2.5}$, and NO_x (the substances are given in decreasing order). Emissions are originating from burning natural gas; H_2SO_4 production and burning lignite and hard coal for electricity production.

For global warming category, evaporation emits CO_2, fossil and land transformation and CH_4; the processes responsible of such emissions are burning natural gas for steam production. For the same category, end-of-pipe treatment methods CO_2, fossil and CH_4; the processes responsible of such emissions are burning lignite and hard coal and H_2SO_4 production.

Finally, non-renewable energy is calculated for utilizing natural gas, hard and brown coal for end-of-pipe treatment and evaporation. Processes are related to extraction and production of these fuels.

In Table 21, scores of end-of-pipe treatment and evaporative recovery based on midpoint impact categories are given.

Table 21. Scores of end-of-pipe treatment and evaporative recovery based on midpoint impact categories

Midpoint Impact Category	**Score (End-of-Pipe Treatment)**	**Score (Evaporation with NG)**
Carcinogens	9.98E-07	8.33E-07
Non-carcinogens	2.19E-06	2.8E-06
Respiratory inorganics	6.51E-05	7.44E-05
Ionizing radiation	6.35E-07	6.26E-07
Ozone layer depletion	1.02E-08	1.36E-08
Respiratory organics	3.01E-08	4.01E-08
Aquatic ecotoxicity	3.59E-07	3.16E-07
Terrestrial ecotoxicity	3.56E-06	2.83E-06

Table 21. (Cont'd)

Terrestrial acid/ nutrification	8.84E-07	9.89E-07
Land occupation	1.86E-07	1.82E-07
Aquatic acidification	0	0
Aquatic eutrophication	0	0
Global warming	7.95E-05	9.89E-05
Non-renewable energy	0.000105	0.000127
Mineral extraction	3.98E-09	3.95E-09

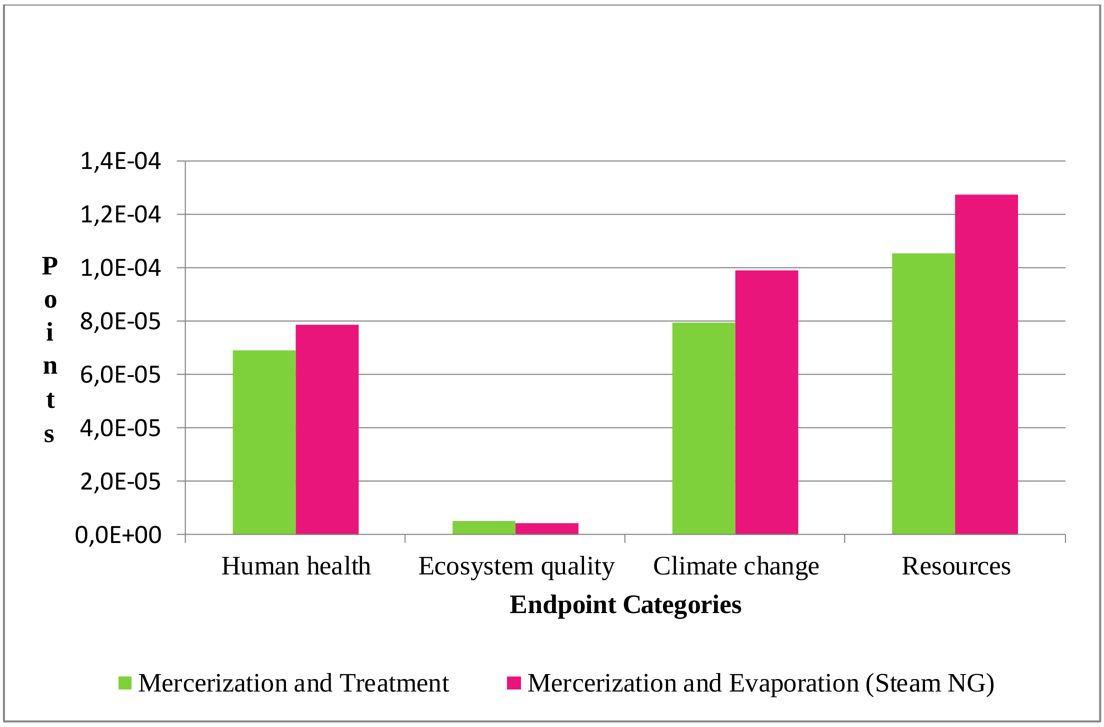

Figure 20. Comparison of end of pipe treatment and evaporation based on endpoint impact categories

In Figure 21, end-of-pipe treatment and evaporation are compared in terms of endpoint categories. Human health, climate change and resources are the categories where evaporation has higher scores. For ecosystem quality, end-of-pipe treatment has higher scores. However these scores are negligible compared to scores of other endpoint categories. In the Table 22, scores of end-of-pipe treatment and evaporative recovery based on endpoint impact categories are given.

Table 22. Scores of end-of-pipe treatment and evaporative recovery based on endpoint impact categories

Endpoint Category	**Score (End-of-pipe treatment)**	**Score (Evaporation)**
Human health	6.9E-05	7.87E-05
Ecosystem quality	4.99E-06	4.31E-06
Climate change	7.95E-05	9.89E-05
Resources	0.000105	0.000127

4.5. Comparison of End-of-Pipe Treatment with Evaporative Recovery Utilizing Light Fuel Oil for Steam Production

In this part, end-of-pipe treatment is compared with evaporative recovery using steam produced with light fuel oil. Like the previous comparisons, respiratory inorganics, global warming and mineral extraction are significant impacts resulting from end-of-pipe treatment and evaporation. Details are given in Figure 22.

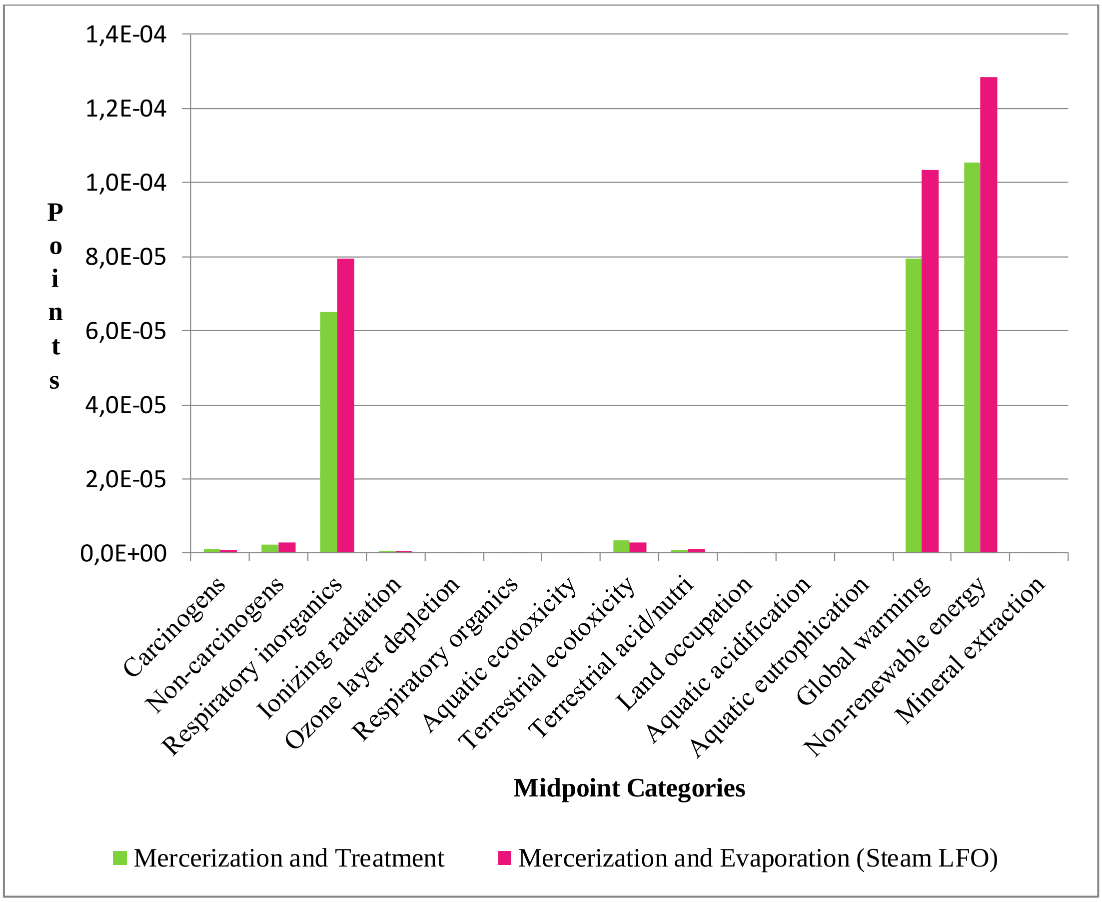

Figure 21. Comparison of end-of-pipe treatment and evaporation based on midpoint impact categories

For respiratory inorganics category, evaporation emits $PM_{2.5}$, SO_2, SO_x, and NO_x; the emissions result from burning lignite and natural gas for electricity production and light fuel oil for steam production. End-of-pipe treatment emits SO_2, SO_x, $PM_{2.5}$, and NO_x (the substances are given in decreasing order). Emissions are originating from burning natural gas; H_2SO_4 production and burning lignite and hard coal for electricity production.

For global warming category impacts are due to emission of CO_2, fossil, CO_2, land transformation and CH_4. The emissions are resulting from burning lignite and natural gas for electricity production and light fuel oil usage for steam production. For the same category end of pipe treatment emits CO_2, fossil and CH_4. Processes responsible for such impact are burning lignite and hard coal and production of H_2SO_4.

Non-renewable energy category both end-of-pipe treatment and evaporation utilizes lignite, hard coal and natural gas and the processes that cause this effect is mining activities for fuel obtainment. H_2SO_4 production for neutralization is another process that uses non-renewable energy. In Table 23, scores of end-of-pipe treatment and evaporation per midpoint impact category are given.

Table 23. Scores of end-of-pipe treatment and evaporation per midpoint impact category

Midpoint Category	**Score (End-of-pipe treatment)**	**Score (Evaporation)**
Carcinogens	9.98E-07	8.65E-07
Non-carcinogens	2.19E-06	2.8E-06
Respiratory inorganics	6,51E-05	7.95E-05
Ionizing radiation	6.35E-07	6.26E-07
Ozone layer depletion	1.02E-08	1.36E-08
Respiratory organics	3.01E-08	4.2E-08
Aquatic ecotoxicity	3.59E-07	3.16E-07
Terrestrial ecotoxicity	3.56E-06	2.82E-06
Terrestrial acid/ nutrification	8.84E-07	1.11E-06
Land occupation	1.86E-07	1.82E-07
Aquatic acidification	0	0
Aquatic eutrophication	0	0
Global warming	7.95E-05	0.000105
Non-renewable energy	0.000105	0.000127
Mineral extraction	3.98E-09	3.83E-09

In Figure 23, end-of-pipe treatment and evaporation are compared in terms of endpoint categories. The most stress is put on resources category.

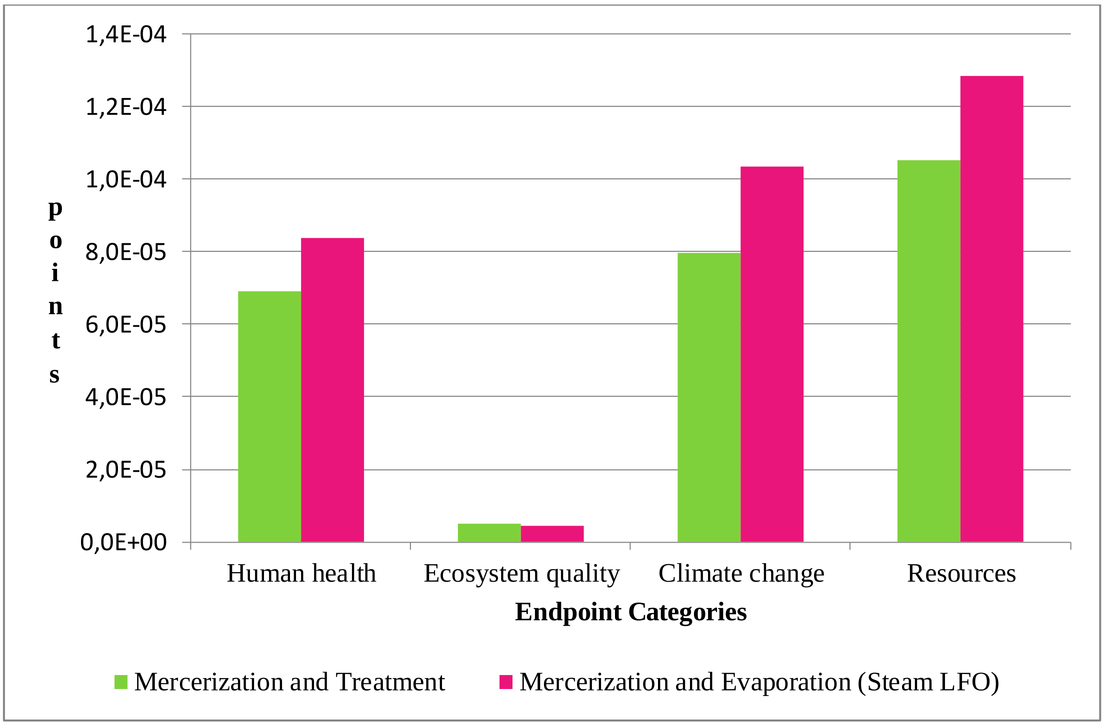

Figure 22. Comparison of end -of- pipe treatment and evaporation per endpoint impact category

Human health, climate change and resources are the categories where evaporation has higher scores. For ecosystem quality, end-of-pipe treatment has higher scores. However these scores are negligible compared to scores of other endpoint categories. In Table 24, scores of end-of-pipe treatment and evaporation per midpoint impact category are given.

Table 24. Scores of end-of-pipe treatment and evaporation per midpoint impact category

Endpoint Category	**Score (End-of-pipe treatment)**	**Score (Evaporation)**
Human health	6.9E-05	8.39E-05
Ecosystem quality	4.99E-06	4.42E-06
Climate change	7.95E-05	0.0001
Resources	0.0001	0.0001

4.6. Single Score Points of Mercerization, End-of-Pipe Treatment and Evaporative Recovery

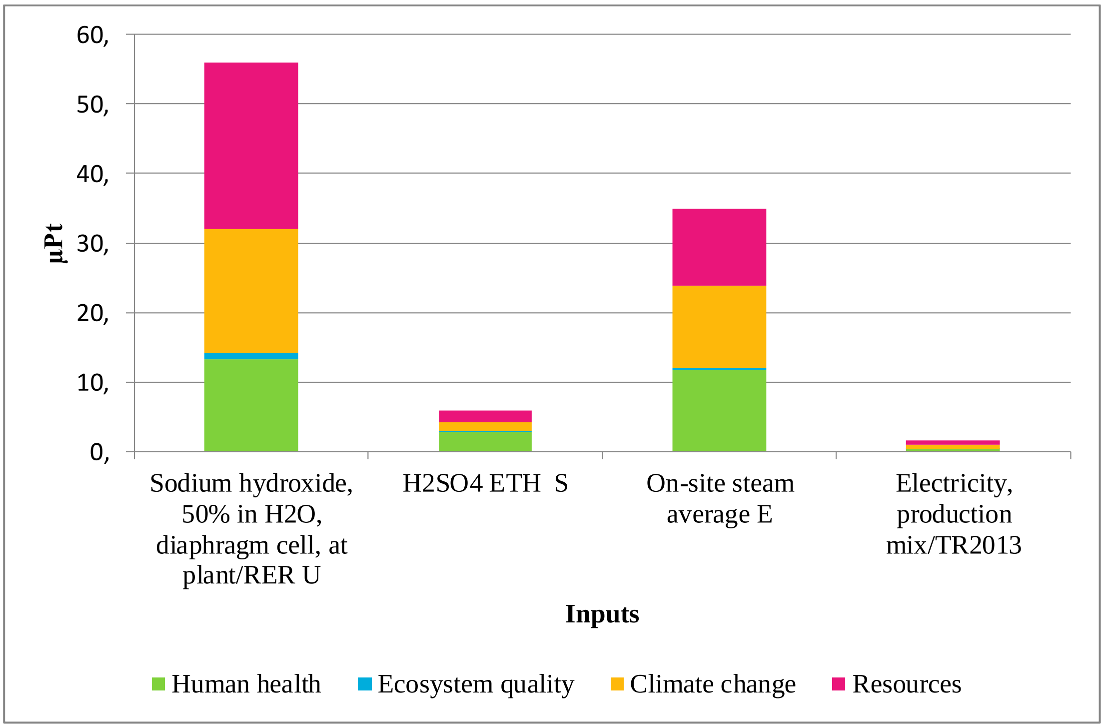

Figure 23. Single score for mercerization process

Single score for mercerization is shown in Figure 24, NaOH production has the greatest score, and it is seen in the Figure 24 that its main impact is on resources. After NaOH production, steam production has the highest score; it seems to be having impact equally on human health, climate change and resources; however the greatest score belongs to climate change. In Table 25, points of mercerization process are given.

Table 25. Single score of mercerization

	Human health	Ecosystem quality	Climate change	Resources
Sodium hydroxide	13.2	1.0	17.8	23.8
H_2SO_4	2.8	0.2	1.2	1.6
On-site steam	11.8	0.2	11.8	11.1
Electricity	0.3	0.006	0.5	0.6

As seen in Table 25, greatest score is in resources category and it is originating from sodium hydroxide production. Sodium hydroxide production is also affecting human health and contributes to climate change.

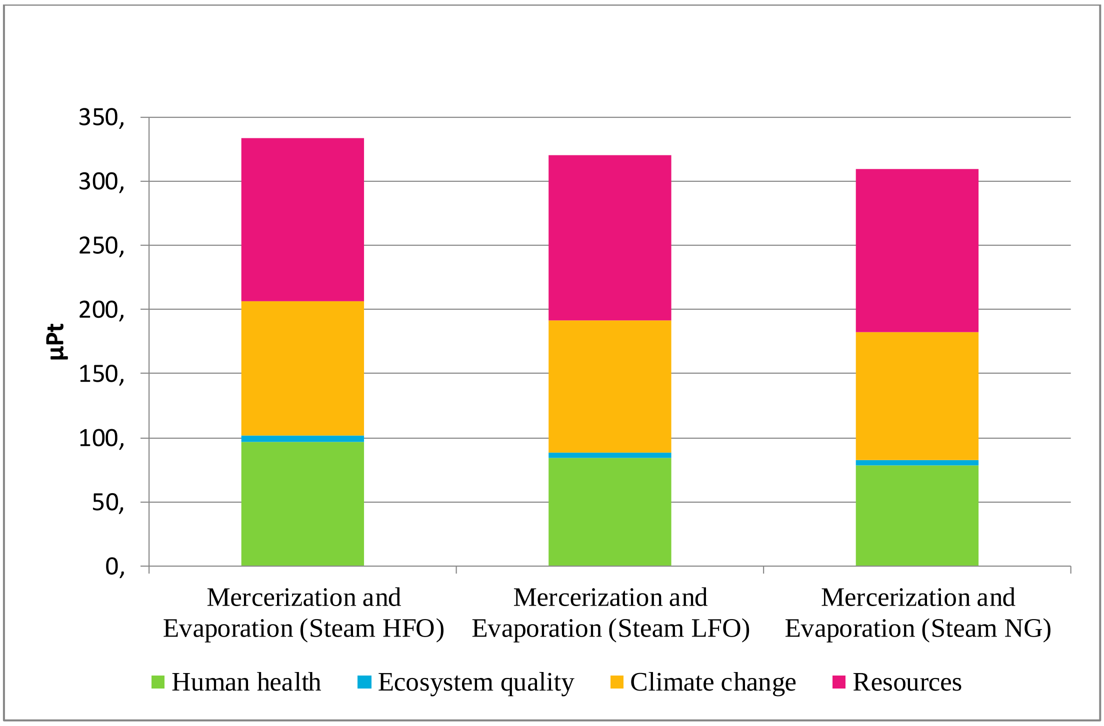

Figure 24. Comparison of evaporation scenarios based on steam production

Single scores of evaporation methods are represented in Figure 25. The comparison is made based on fuel used for steam production during evaporation process. In the industry, mainly used fuels are considered which are heavy fuel oil, natural gas and light fuel oil. Evaporation done with steam which is produced by using heavy fuel oil has the greatest impact on the environment among the rest of others. And evaporation done with steam which is produced by using natural gas is the most environmentally friendly method.

Table 26. Scores of evaporative recovery scenarios

Evaporation Method based on Fuels	**Score**
Mercerization and Evaporation (Steam HFO)	333.3
Mercerization and Evaporation (Steam LFO)	320
Mercerization and Evaporation (Steam NG)	309

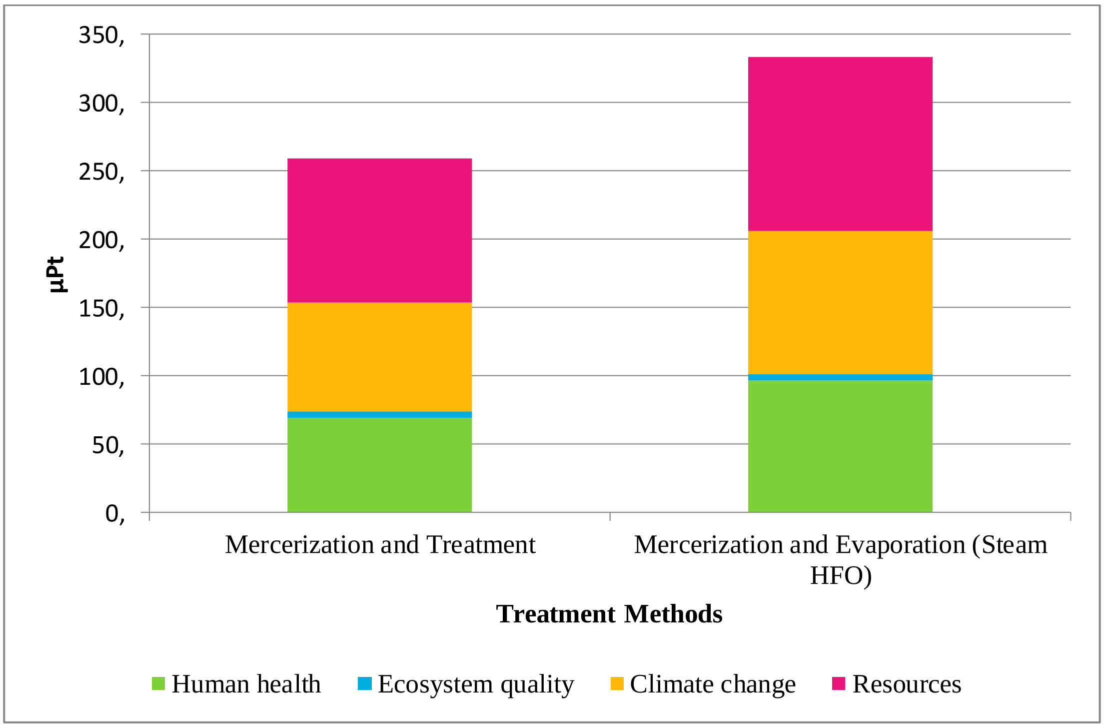

Figure 25. Comparison of single scores of end-of-pipe treatment with evaporative recovery

Comparison of end of pipe treatment and evaporation done with steam which is produced by using heavy fuel oil is shown in Figure 26. Score of end-of-pipe treatment is 259 while score of evaporation is 333.3. Evaporation has higher score than end-of-pipe treatment. This is due to amount of emissions made during combustion of fuels, which are mentioned several times in the previous sections, for electricity production, steam production and production of chemicals used for mercerization and neutralization (i.e. NaOH and H_2SO_4)

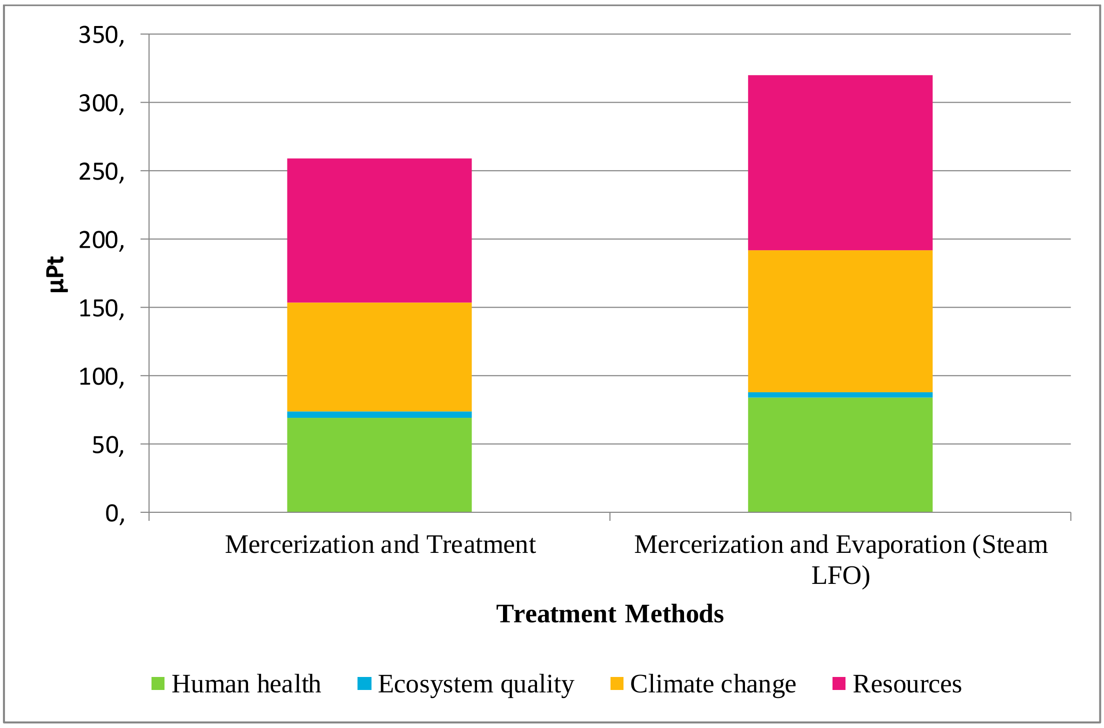

Figure 26. Comparison of end -of- pipe treatment and evaporation

Comparison of end of pipe treatment and evaporation done with steam which is produced by using light fuel oil is shown in Figure 27. End-of-pipe treatment is more environmentally friendly than evaporation. The scores of the treatment methods are 259 and 320, respectively.

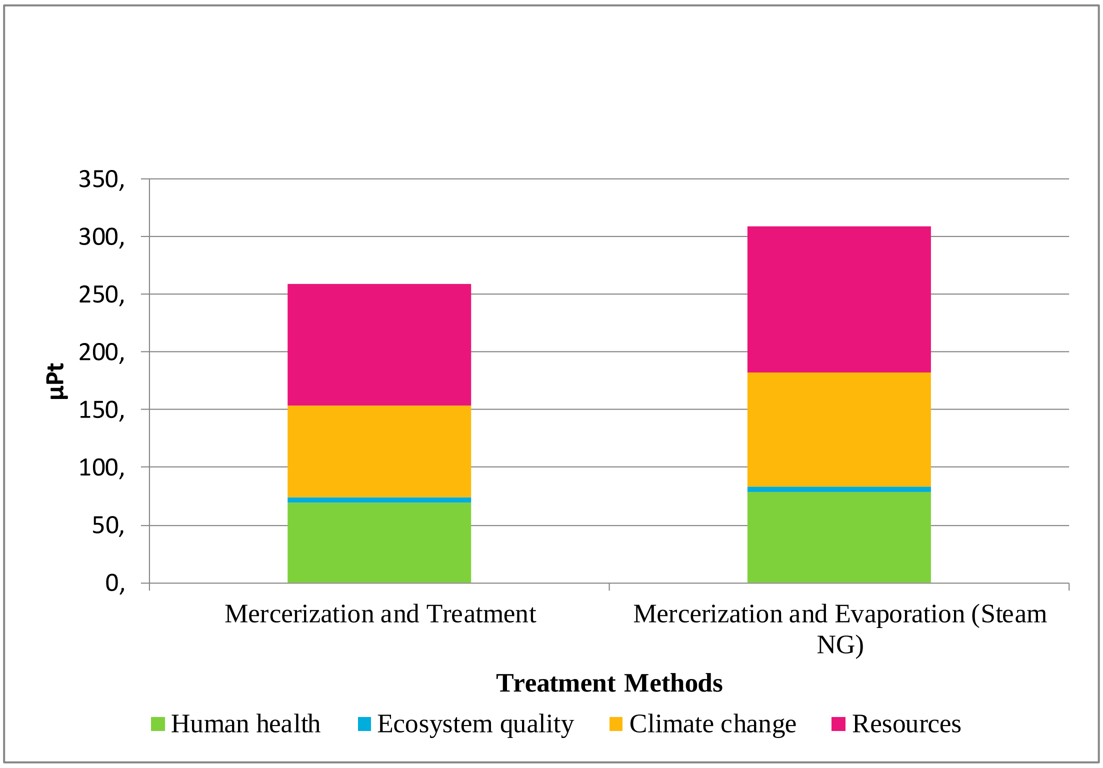

Figure 27. Comparison of end -of- pipe treatment and evaporation

Comparison of end of pipe treatment and evaporation done with steam which is produced by using natural gas is shown in Figure 28. End-of-pipe treatment is more environmentally friendly than evaporation. The scores of the treatment methods are 259 and 309, respectively. The difference between points of end-of-pipe treatment and evaporation done with steam which is produced by using natural gas is smaller compared with the other evaporative recovery methods. During evaporation done with steam which is produced by using natural gas, less gaseous compounds are emitted compared to other evaporation methods. Study Plant 2 uses natural gas for steam production, which has less environmental impacts compared to other evaporation scenarios. Scores stated in this section are considered as the final result of the present study.

4.7. Financial Comparison of Evaporation and End-of-Pipe Treatment

In this part of the thesis, a financial evaluation is presented to consider the options of end-of-pipe treatment and evaporative recovery. Taking the basis as 1 ton of weak lye, and considering the data given in Chapter 3, the investment and operational costs for the options considered over a 20 year period (NPV, applying a discount rate of 5.5% per annum) have been calculated. The financial valuations assume that distilled water and heat owned by hot water exhausted from evaporative recovery are reused along with strong lye. Therefore, the economical values of these recyclables are considered as revenues, and possible revenues for both of the scenarios are estimated. The cost of these recovered materials and heat are calculated as if they were bought instead of being recovered. And the result is divided by 20 to find the revenue per ton of material/heat recovered. In Table 27, results of economic analysis are presented.

Table 27. Results of economic analysis

	Evaporative Recovery	**End-of-pipe Treatment**
REVENUES		
Strong lye	7.946.400	0
NPV	4.746.528	0
€/ton	**9.13**	**0**
Distilled Water	1.682.625	0
NPV	1.005.062	0
€/ton	**1.93**	**0**
Hot water	10.370.430	0
NPV	6.194.445	0
€/ton	**11.91**	**0**
Total Revenue	19.999.455	0
NPV	11.946.036	0

Table 27. (Cont'd)

€/ton	**23.0**	**0**
INVESTMENT	400.000	188.235
NPV	380.048	178.846
€/ton	**0.73**	**0.34**
OPERATION AND MAINTENACE	880.709	206.118
NPV	526.063	2.585.474
€/ton	**1.01**	**4.97**
NET COST (NPV), €	11.039.925	-2.764.319
Net Unit cost, (NPV) €/ton	**21.2**	**-5.3**

Recalling the equation 1, NPV values are calculated as:

$$NPV = \frac{[B(t) - C(t)]}{(1+i)^t} \quad (1)$$

Total revenue of evaporation is 23 €/ton, while total costs are calculated as 0.73 €/ton and 1.01 €/ton, for investment and operation & maintenance, respectively. Thus, benefits are 23 €/ton while costs are 1.74 €/ton.

Net present value of evaporation is 23-1.74= 21.2 €/ton,

Total revenue of end-of-pipe treatment is 0 €/ton, while total costs are calculated as 0.34 €/ton and 4.97 €/ton, for investment and operation & maintenance, respectively. Thus, benefits are 0 €/ton while costs are 5.3 €/ton.

Net present value of end-of-pipe treatment is 0-5.3 = -5.3 €/ton.

NPV of end-of-pipe treatment is smaller than zero while NPV of evaporation is bigger than zero. The result means, evaporation is favorable in economical means.

CHAPTER 5

CONCLUSION

Textile industry is a water-intensive industry that emits vast amounts of severely polluted wastewater. As a process of textile industry, mercerization emits highly alkaline wastewater that requires neutralization and further treatment and after neutralization, this wastewater is then combined with other waste streams and then treated in wastewater treatment plant. This wastewater treatment method ultimately gives a variety of burdens to the environment.

Highly alkaline mercerization wastewater can be managed in several ways. The Textile Industry BREF Document suggests its evaporative recovery as a BAT.

In the present study, environmental effects due to evaporation of mercerization wastewater are considered and evaluated. Data regarding evaporation are assessed with SimaPro, LCA software. During evaporation, wastewater is passed through four stages of condensers and distilled, and therefore large amount of heat energy is employed. Heat energy is required for steam production. Steam can be produced by using several fuels. In this thesis work, three scenarios are established based on fuel used for steam production. The fuels under consideration are: heavy fuel oil, light fuel oil and natural gas.

The comparison done between end-of-pipe treatment method and evaporation scenarios indicated that end-of-pipe treatment is more environmentally friendly than evaporative recovery of weak lye from mercerization process with much less impacts on the end-point impact categories of human health, climate change and resources. Steam production appeared as responsible for the main environmental burden caused by the evaporation process. Fuels used and emissions generated from steam production are the causes of the environmental effects.

The results showed that steam production is the major step in the process of evaporation responsible of the adverse impacts on the environment. Due to combustion of fuels during heating process for steam generation, respiratory inorganics are emitted to air and they give damage to human health. Also, some gaseous emissions causing global warming contribute to climate change, and moreover fuels used for steam production process also found out to be giving damage to the environment by depleting energy sources, thus putting stress on limited non-renewable energy sources.

Financial analysis of these systems showed that evaporative recovery is economically feasible. Evaporative recovery has the opportunity to recover sodium hydroxide, heat and distillate; recovery provides turn possible expenses into revenue. End-of-pipe treatment does not have such opportunity, it only has expenses and it is considered as a financial burden by industries. Taking account of the fact that evaporation is economically feasible, it is recommended for textile producers to segregate the alkaline mercerization wastewater to subject to evaporative recovery.

REFERENCES

1. Bilim Sanayi ve Teknoloji Bakanlığı. (2014). *Tekstil Hazır Giyim ve Deri Ürünleri Sektörleri Raporu*, 2014/1, http://sanayipolitikalari.sanayi.gov.tr/Public/SectorReports/10, Last visited December 2014

2. European Commission, (2003). *Integrated pollution prevention and control (ippc) reference document on best available techniques for textiles industry,* Retrieved from http://eippcb.jrc.ec.europa.eu/reference/txt.html, last visited on August 2013

3. Babu, B., & Parande, A. (2007). *An overview of wastes produced during cotton textile processing and effluent treatment methods*. The Journal of Cotton Textile, 11, 110-122.

4. Environmental Protection Agency. (1997). *Office of compliance sector notebook project: profile of the textile ındustry*. Washington.

5. Özturk E., Yetiş Ü., Dilek F.B., Demirer G.N,(2009). *A chemical substitution study for a wet processing textile mill in Turkey*, Journal of Cleaner Production 17 239–247.

6. Bisschops Spanjers H. (2003). *Literature review on textile wastewater characterization* Environmental Technology, Vol. 24. pp 1399-1411.

7. Horne, R.,&Grant, T. (2009). *Life cycle assessment: origins, principles and context*. Life Cycle Assessment Principles, Practice, and Prospects. Collingwood.

8. Hämäläinen, R. P. (1997). *How to benefit from decision analysis in environmental life cycle assessment (LCA*). European Journal of Operational Research, 279-294.

9. Kadoğlu, H. (nd). *Temel tekstil teknolojisi, lifler, iplik oluşumu*. Lecture conducted from Ege İhracatçı Birlikleri, Tekstil Mühendisleri Odası.

10. Rouette H.K., (2000). *Encyclopedia Of Textile Finishing* Retrieved from: https://app.knovel.com/web/view/swf/show.v/rcid:kpETF00001/cid:kt003VQMY1/viewerType:pdf/root_slug:encyclopedia-

textile?cid=kt003VQMY1&page=4&b-q=Encyclopedia%20of%20Textile%20Finishing&sort_on=default&b-subscription=TRUE&b-group-by=true&b-search-type=tech-reference&b-sort-on=default&b-toc-cid=kpETF00001&b-toc-root-slug=encyclopedia-textile&b-toc-url-slug=front-matter&b-toc-title=Encyclopedia%20of%20Textile%20Finishing, Last visited May 2014

11. Pakistan Textile Journal. *Textile Finishing Industry: Facing high cost of production.* (n.d.). Retrieved August 22, 2015.

12. Cooper, S. (1978). *Water Pollution. In The Textile Industry Environmental Control and Energy Conservation* New Jersey: Noyes Data Corporation.

13. Vandevivere, P., Bianchi, R., & Verstraete, W. (1998). *Review: Treatment and Reuse of Wastewater from the Textile Wet-Processing Industry*: *Review of emerging technologies*. Journal of Chemical Technology & Biotechnology. 72, 289-302.

14. Correia V. M., Stephenson T., Judd S. S., (1994). Characterization of textile waste water- a review. Environmental Technology. 15, 10, 917-929.

15. Orhon D, Kabdasli I, Germirli Babuna F, Sozen S, Dulkadiroglu H, Dogruel S, (2003). *Wastewater Reuse for the Minimization of Fresh Water Demand in Coastal Areas-Selected Cases from The Textile Finishing Industry*. Journal of Environmental Science and Health A 38, 1641–57.

16. Department for Environment, Food And Rural Affairs. (2008). *Assessment of the implementation of the IPPC Directive in the UK* London, UK:Queen's Printer and Controller of HMSO

17. Marcucci, M., Nosenzo, G., Capannelli, G., Ciabatti, I., Corrieri, D., & Ciardelli, G. (2001). *Treatment and reuse of textile effluents based on new ultrafiltration and other membrane technologies*. Desalination, *138*(1-3), 75-82.

18. Rahman, Atikur, and Nymul Ehsan Khan. (2006). *Study of an evapotarion system for sodium hydroxide solution*. Journal of Chemical Engineering, 35-36.

19. Woolridge A., Ward G.D., Phillips P.S., Collins M., Gandy S. (2006). *Life cycle assessment for reuse/recycling of donated waste textiles compared to use of virgin material: An UK energy saving perspective* Resources, Conservation and Recycling 46 94–103.

20. Kalliala E.M. Nousiainen P. (1999). *Environmental profile of cotton and polyester cotton fabrics* AUTEX Research Journal 1, 1

21. Beck A., Scheringer M., Hungerbühler K. ,(2000). *Fate modeling with LCA* International Journal of Life Cycle Assessment 6, 6, 335-344.

22. Van der Velden N.M., Patel M.K., Vogtlander J.G. (2014). *LCA benchmarking study on textiles made of cotton, polyester, nylon, acryl, or elastane* International Journal of Life Cycle Assessment 19, 331–35.

23. Sundin M., (2002). *From the cradle to the gate. A life cycle inventory on cotton trousers*. Thesis. Norrköping/ Linköpings Universitet.

24. Pfister S., Koehler A., Hellweg S.(2009). *Assessing the environmental impacts of freshwater consumption in LCA* Environmental Science and Technology 43, 4098–4104.

25. Güngör A. Palamutçu S., İkiz Y.(2009). *Pamuklu Tekstiller Ve Çevre: Bir Bornozun Yaşam Döngü Değerlendirmesi* Tekstil ve Konfeksiyon 3,197-205

26. Introduction to LCA, SimaPro Manual, Pré Consultants, 2008

27. EPA, (2006). *Life cycle assessment: principles and practice* (EPA/600/R-06/060). Ohio: SAIC.

28. Ölmez, Gülnur. (2011). *Comparison of Sub-Processes and Final Products of Iron and Steel Production with Life Cycle Assessment*. Thesis. Ankara/ Middle East Technical University. Retrieved From http://etd.lib.metu.edu.tr/upload/12613920/index.pdf, last visited March 2015.

29. Bare J.C., Hofstetter P., Pennington D.W., de Haes H.A.U.(2000) *Midpoints versus endpoints: The sacrifices and benefits*. The International Journal of Life Cycle Assessment 5, 6, 319-326

30. https://www.pre-sustainability.com/ , Last visited January 2016

31. SimaPro Database Manual Methods Library, Pré Consultants, 2008

32. Humbert S., Margni M., Jolliet O., Impact 2002+: User Guide, 2005

33. Yılmaz M., (2012). *The energy potential of Turkey and its importance of renewable energy sources in terms of electricity production*. Ankara Üniversitesi Çevrebilimleri Dergisi. 4 (2), 33-54.

34. Biyo (Katı) Yakıt (nd). Retrieved from: http://biyosfer.com.tr/biyo-kati-yakit.html. Last visited March 2015

35. TKİ (2010). *Kömür (linyit) sektör raporu 2009*: Ankara

36. Savin I., Butnaru S. (2008) *Wastewater characteristics in textile finishing mills*. Environmental Engineering and Management Journal 7, 6, 859-864.

37. Asthma and Air Pollution (Air Pollution Causes Asthma Attacks, Health Effects of Air Pollution), http://www.nrdc.org/health/effects/fasthma.asp, Last visited October 2015

38. Brown T. (2007). Engineering Economics and Economic Design for Process Engineers, CRC Press, New York

39. Kuyucak N. (nd). *Lime neutralization treatment plant cost estimate*. Retrieved from http://www.minem.gob.pe/minem/archivos/file/dgaam/publicaciones/curso_cierreminas/01_Gerencial/10_Tratamiento%20de%20Aguas/GerTratAgu-L2_Cost%20Estimate.pdf, Last visited November 2015

40. Berndt E., Doyle J., Chapman M., Stoker T. *Comparing economic and financial impacts over the life of proposed projects* [Lecture notes] Retreived from: http://ocw.mit.edu/courses/civil-and-environmental-engineering/1-011-project-evaluation-spring-2011/lecture-notes/MIT1_011S11_lec05.pdf Last visited December 2015

41. DEPweb. (n.d.) What is sustainable development? Retreived from http://www.worldbank.org/depweb/english/sd.html Last visited December 2015

APPENDIX A

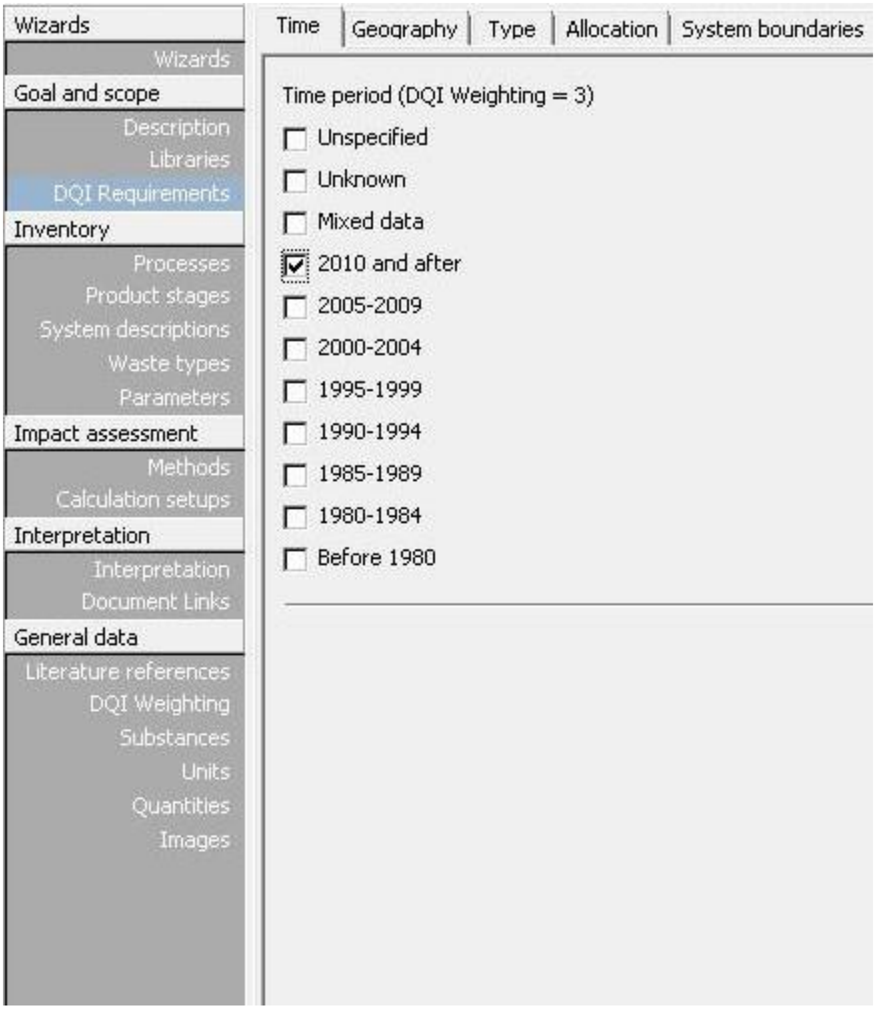

Figure 28. DQI regarding time

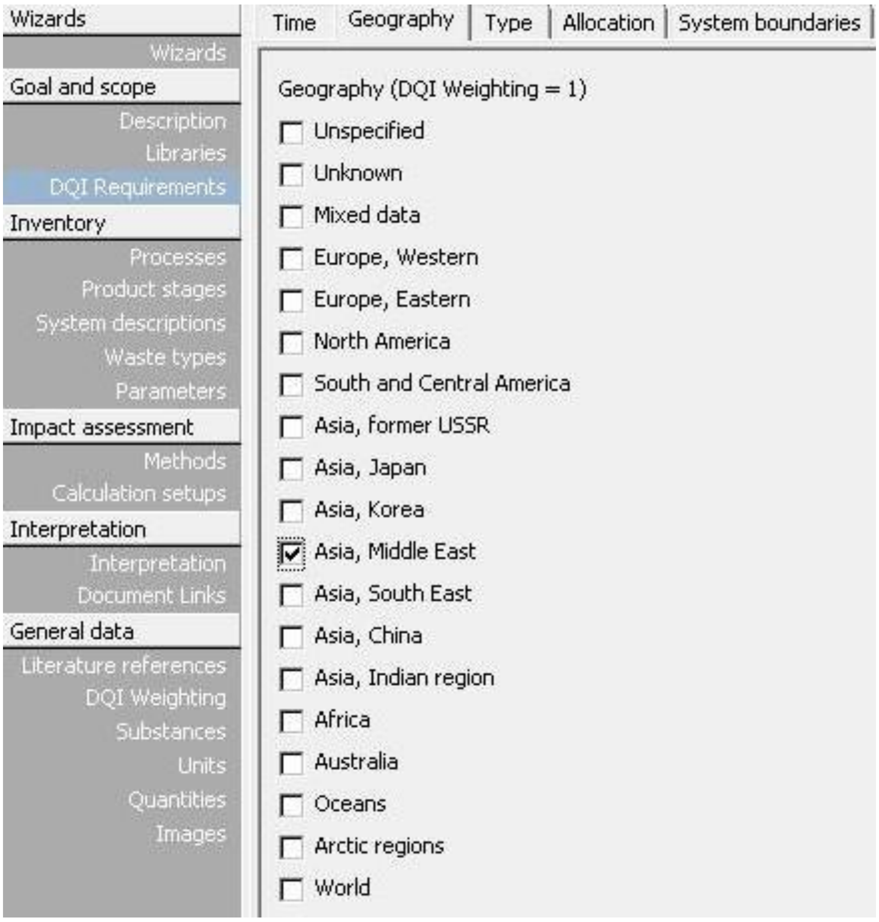

Figure 29. DQI regarding geography

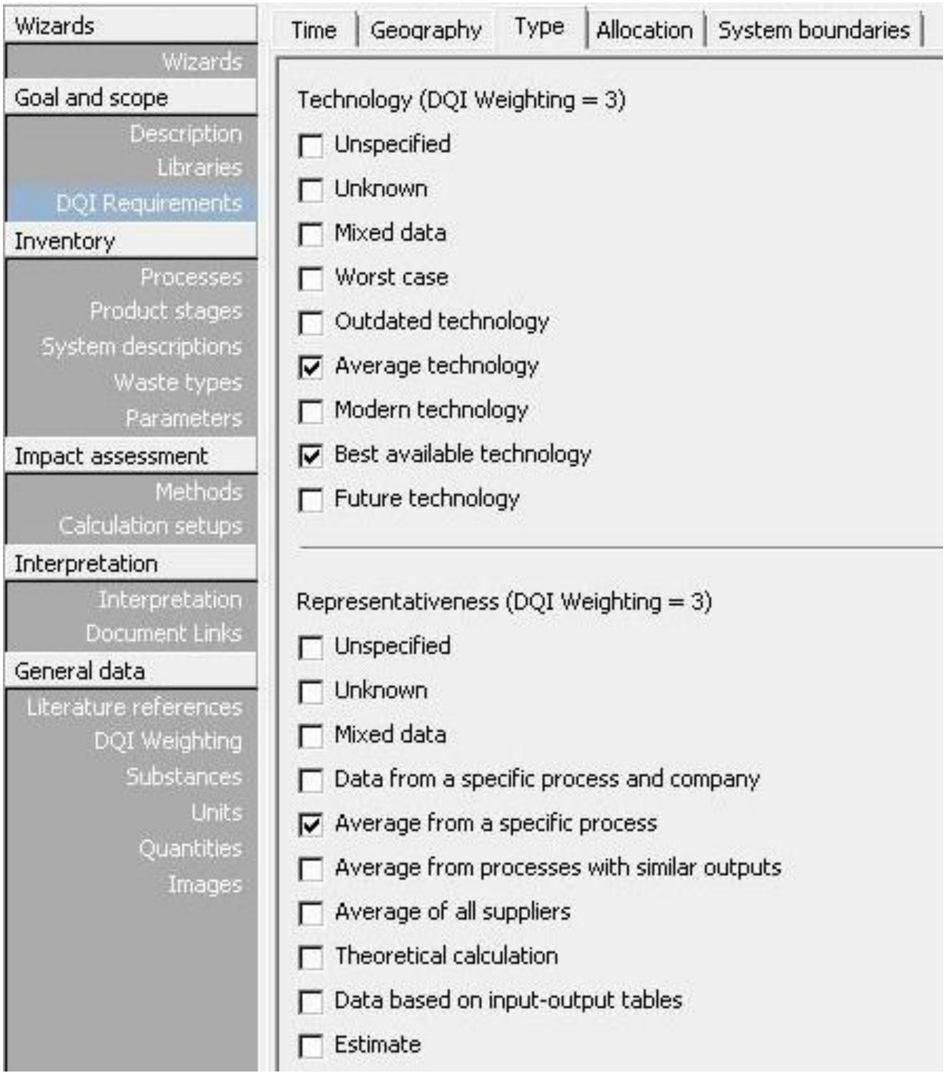

Figure 30. DQI regarding type

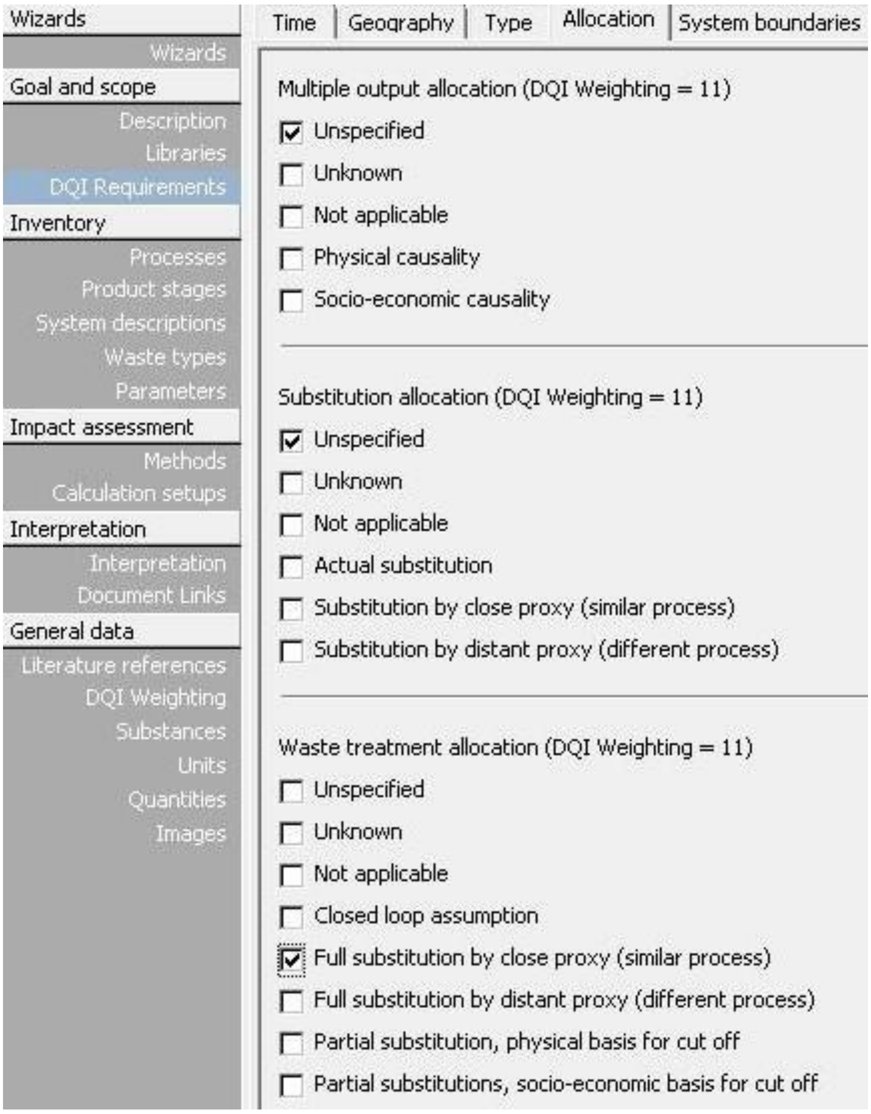

Figure 31. DQI regarding allocation

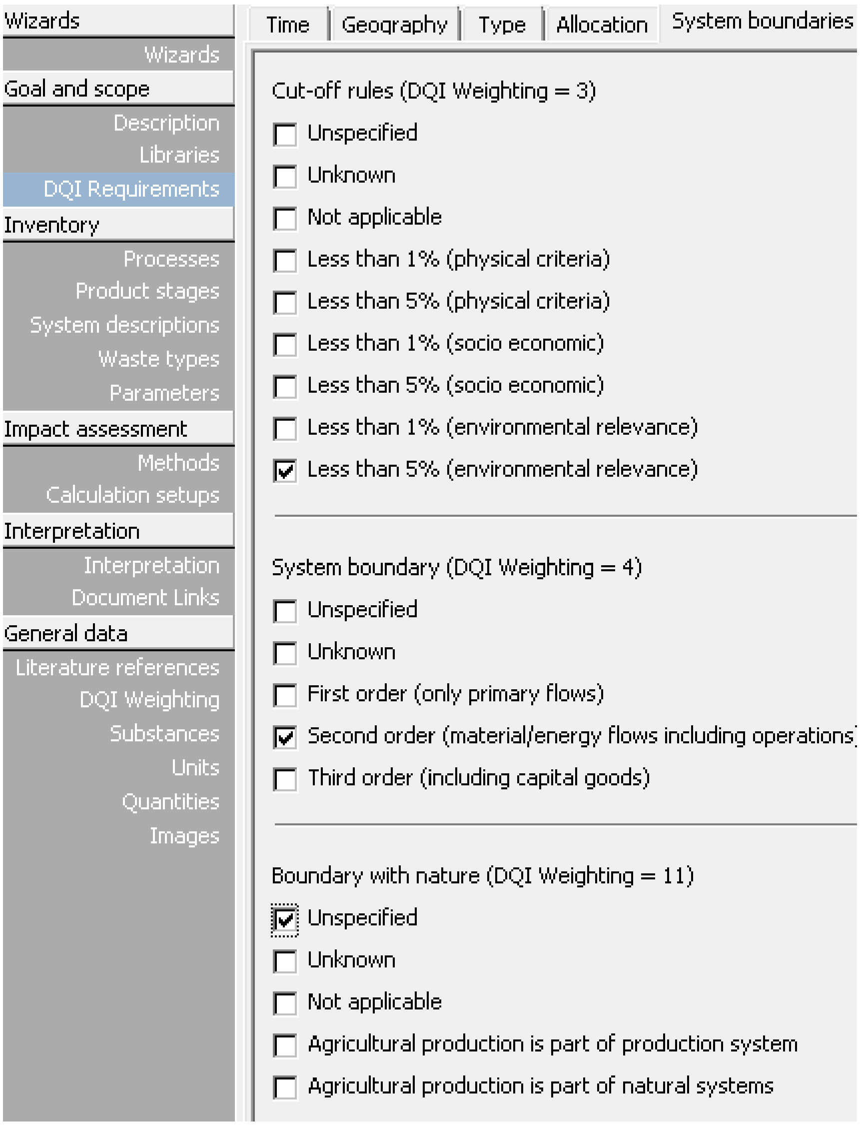

Figure 32. DQI regarding system boundaries