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Life Cycle Assessment and Technical Performance of Recycled and Bio-based Plastics

Thesis submitted in partial fulfilment of the requirements for the degree of Master of Science in Technology
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Abstract of master's thesis

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Abstract

Environmental impacts of products can be reduced, for example, by reducing materials or by selecting materials, whose production causes low environmental impacts. In this thesis is studied, whether it is possible to reduce environmental impacts of a plastic product by using recycled or bio-based plastics. In this case, the environmental impacts refer to the greenhouse gas emissions and primary energy demand.

Essential recycling methods of plastics are presented. The definitions and manufacturing of bio-based plastics are also discussed. Environmental impacts of recycled and bio-based plastics are assessed with life cycle assessment (LCA) method. In addition to the LCA, material tests are used to evaluate suitability of the plastics to be used in base stations of mobile networks. Testing included 6 months outdoor exposure in Finland, Greece and Kenya and also a long-term accelerated aging test at 85 °C and 85 % relative humidity. Testing samples were made with an actual production mould. Studied materials were polycarbonate (PC), polycarbonate-polyethylene terephthalate (PC/PET) blend, bio-based polyamide (PA) 410 and bio-based glass fibre reinforced polytrimethylene terephthalate (PTT).

Results of LCA show that recycling of plastics reduces significantly environmental impacts of material production. If the plastic cover of a base station contains 100 % recycled PC, emissions and primary energy demand of plastics production are reduced by 86 %. Substituting 30 % of virgin PC by recycled PC reduces the environmental impacts of plastic production by 23 %. The effect of bio-based material content on the environmental impacts is not as straightforward. Depending on the plastic grade, the environmental impacts of the production of bio-based plastics are higher or lower than those of virgin PC. Based on the material testing, the properties of recycled PC are comparable to those of virgin PC. The bio-based plastics also performed well in the testing, and based on these results they provide sufficient properties to the plastic cover.

Keywords Life Cycle Assessment; Recycling of plastics; Mechanical recycling; Bio-based plastics; Carbon footprint

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Tiivistelmä

Tuotteiden ympäristövaikutuksia voidaan pienentää esimerkiksi vähentämällä materiaalien määrää tai valitsemalla materiaaleja, joiden valmistus tuottaa pienet ympäristövaikutukset. Tässä työssä tutkitaan, voidaanko kierrätysmuovien tai biopohjaisten muovien käytöllä vähentää muovituotteen ympäristövaikutuksia. Ympäristövaikutuksilla tarkoitetaan tässä tapauksessa kasvihuonekaasupäästöjä ja primäärienergian kulutusta.

Työssä esitetään keskeisimmät muovin kierrätysmenetelmät sekä selvitetään, mitä muovien biopohjaisuus tarkoittaa ja miten biopohjaisia muoveja valmistetaan. Kierrätettyjen ja biopohjaisten muovien valmistuksen ympäristövaikutuksia selvitetään standardisoidulla elinkaariarviointi-menetelmällä. Elinkaariarvioinnin lisäksi muovien soveltuvuutta mobiiliverkkojen tukiasemien kuorimateriaaliksi arvioidaan testien avulla. Testiohjelmaan kuuluu esimerkiksi 6 kk:n ulkoilmatestaus Suomessa, Kreikassa ja Keniassa sekä pitkäkestoinen vanhennustesti 85 °C:n lämpötilassa ja 85 % suhteellisessa kosteudessa. Testejä varten tutkituista muoveista ruiskupuristettiin todellisen tukiaseman suojamuoveja. Tutkittavat muovit ovat polykarbonaatti (PC), polykarbonaatti-polyeteeni tereftalaatti seos (PC/PET), biopohjainen polyamidi (PA) 410 ja biopohjainen, lasikuidulla lujitettu polytrimeteeni tereftalaatti (PTT).

Työssä todettiin, että muovien kierrätys vähentää selvästi muovinvalmistuksen kasvihuonekaasupäästöjä sekä energian kulutusta. Jos tukiaseman suojakuori tehdään kokonaan kierrätetystä polykarbonaatista, muovin valmistuksen päästöt ja energian kulutus vähenevät 86 %. Korvaamalla 30 % neitseellisestä materiaalista kierrätetyllä, muovin valmistuksen ympäristövaikutukset laskevat 23 %. Biopohjaisen materiaalin vaikutus ympäristövaikutuksiin ei ollut yhtä suoraviivainen. Riippuen muovilaadusta biopohjaisten muovien valmistus aiheuttaa suuremmat tai pienemmät ympäristövaikutukset kuin neitseellinen polykarbonaatti. Tehtyjen testien perusteella kierrätetty PC on ominaisuuksiltaan lähellä neitseellistä PC:tä. Myös biopohjaiset muovit suoriutuivat testeistä ilman suuria ongelmia ja tarjoavat suojakuorelle vaadittavia ominaisuuksia.

Avainsanat Elinkaariarviointi; Muovien kierrätys; Mekaaninen kierrätys; Biopohjainen muovi; Hiilijalanjälki

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Heikki Karvinen

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ABBREVIATIONS

BPA	Bis-phenol A
DAB	Diaminobutane
CF	Carbon footprint
CFC	Chlorofluorocarbon
CO_2	Carbon dioxide
GF	Glass fibre
GHG	Greenhouse gas
GWP	Global warming potential
ESC	Environmental stress cracking
FR	Flame retarded
FT IR	Fourier transform infra-red
HCFC	Hydrochlorofluorocarbon
HDPE	High density polyethylene
ICT	Information and communication technology
IPCC	Intergovernmental Portal of Climate Change
ISO	International Organization for Standardization
k_{CO2}	Radiative forcing of carbon dioxide
k_{GHG}	Radiative forcing of greenhouse gas
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LDPE	Low density polyethylene
MEP	Mitsubishi Engineering-Plastics Corporation
NREU	Non-renewable energy usage
PA	Polyamide
PBAT	Polybutylene adipate terephthalate

PBT	Polybutylene terephthalate
PC	Polycarbonate
PCL	Polycaprolactane
PDO	1,3 propanediol
PE	Polyethylene
PET	Polyethylene terephthalate
PFC	Perfluorocarbon
PHA	Polyhydoxyalkanoates
PLA	Polylactic acid
PMMA	Polymethyl methacrylate
PP	Polypropylene
PS	Polystyrene
PPT	Polypropylene terephthalate
PTT	Polytrimethylene terephthalate
PVC	Polyvinyl chloride
PWB	Printed wiring board
rPC	Recycled polycarbonate
rPET	Recycled polyethylene terephthalate
RTI	Relative temperature index
T_g	Glass transition temperature
TH	Time horizon in global warming calculations
tkm	Tonne kilometre
TPA	Terephthalatic acid
UV	Ultraviolet
vPC	Virgin polycarbonate
y_{CO2}	Lifetime of carbon dioxide
y_{GHG}	Lifetime of greenhouse gas

1 INTRODUCTION

Products are traditionally designed to minimize costs and delivery times and maximize production volume. Awareness of environmental problems, such as global warming and the depletion of fossil fuels, has increased among customers, stakeholders and authorities, and therefore many companies aim to decrease environmental impacts of the products. Environmental impacts include, for example, greenhouse gas (GHG) emissions and eutrophication.

This study focuses on the environmental impacts and technical performance of the plastics covers of base stations. Base stations are radio network devices, which provide wireless connections for mobile devices like smartphones, tablets and computers. Base stations are located in masts and buildings and they are used outdoors and indoors. An example of a module base station with a plastic cover is shown in Figure 1.

The function of the plastic cover is to protect the base station from solar radiation, rain and other weather conditions. The grill in the covers allows air to flow into the device to cool it. The cover was selected for this study, since it represents a high production volume plastic part with the typical requirements of an outdoor application. Materials of base stations encounter both tropical and arctic conditions, because the same kind of base stations are used globally.

Figure 1. Nokia Flexi Multiradio 10 Base Station mounted on wall. Base stations are mainly produced from aluminium but they also contain plastics. (Nokia Networks 2014a)

Base stations are mainly produced from aluminium due to its availability, lightness, corrosion resistance and thermal conductivity. The downside of aluminium are the environmental impacts of the virgin aluminium production. Virgin aluminium is extracted from bauxite ore, which is an energy intensive process (Polmear 2006). The environmental impacts are reduced, if less aluminium is used, for example, due to improved design. The environmental impacts of the product can also be lowered, if lighter materials are used. In this case, some parts can be manufactured from plastics. Plastics possess some advantages over metals, such as the possibility to manufacturing complex shapes and control material properties with additives and fillers.

The environmental impacts of material production are also reduced, when recycled materials are used. The production of recycled material causes generally fewer environmental impacts than the production of virgin material (Ashby 2013). Aluminium and other metals are easily reused many times. However, the end-of-life treatment of plastics is not as evolved as that of metals, and plastics are mainly landfilled or incinerated (PlasticsEurope 2013). Plastics are also recycled, but not in the same quantity as metals. In addition to recycling, bio-based plastics may provide an option to reduce the environmental impacts of plastics production. Bio-based plastics reduce the need of petroleum-based raw materials. Recycled and bio-based plastics are already used in consumer products. For example, beverage bottles from polyethylene terephthalate (PET) are successfully recycled. Bio-based plastics are found in various applications such as in drinking cups from polylactic acid (PLA) and automotive and electrical applications from polyamide (PA) 11 (Arkema 2014). PLA is produced by microbial fermentation from starch and PA 11 is made of undecenoic acid derived from castor oil.

In this thesis, technical performance and environmental impacts of recycled polycarbonate (PC), PC/PET blend and bio-based polytrimethylene terephthalate (PTT) and PA 410 are studied. Environmental impacts of material production are compared with the life cycle assessment method (LCA). LCA is a standardized tool which is used to estimate the environmental impacts of the product through its life cycle. General principles of the method are described in standards SFS-EN ISO 14040 (Environmental management. Life cycle assessment. Principles and framework) and 14044 (Environmental management. Life cycle assessment. Requirements and guidelines.) (2006). Selected environmental impact categories are primary energy demand and GHG emissions. The comparison between recycled and bio-based plastics can be difficult, since the materials have clearly different life cycles. Deciding the system boundaries for the LCA is challenging since recycled and bio-based materials can be treated several ways in the LCA (Lighart & Ansems 2012). Other studies also suggest that there may not be a clear win or lose situation (Shen et al. 2010) (Shen et al. 2011) (Vercalsteren et al. 2009).

Environmental attributes do not give information about the physical and mechanical properties of the materials. Low emissions and energy usage of the material production cannot be utilised, if the material is not suitable for the application. Therefore series of tests are conducted to study how the materials perform in the product. Tests contain weathering, aging and chemical resistance tests. Tests are based on international standards and guidelines of plastic and electronic equipment testing. Studied materials should perform in a similar manner as the PC, which is currently used in the products. Improvements in the performance of the product are not within the scope of this study.

2 PLASTICS MATERIALS

Plastics are a group of materials which are produced from polymers and additives. Plastics are formed with pressure and heat and they are produced into fibres, films, bottles, containers and structural parts. Plastic materials can be moulded into very complex shapes and plastics can have mechanical properties comparable to metals. In addition, plastics are lightweight, which makes it possible to reduce the weight of products. Plastics are dielectric, but their electrical and thermal conductivity can be improved by fillers such as carbon, glass and metal fibres and particles (Brydson 1999).

Plastics play an important role in base stations even though metals are the main materials. Plastics are used in connectors, wire insulations, printed wiring boards (PWB), covers and solar shields (Strong 2006). Plastic materials in base stations are mostly PC, polybutylene terephthalate (PBT) and PA. Thermoset epoxies are used in PWBs. PC is used in structural parts such as covers, solar shields, LED pipes and fan casings. PBT and PA are used in insulations since these materials have high dielectric strength.

2.1 Thermoplastics and thermosets

Polymers are classified into thermoplastics and thermosets (Seppälä 2005). Thermoplastics polymers such as PA and PC can be moulded several times. Polymer chains in thermoplastics are connected with hydrogen bonds which allow material to flow under stress at high temperatures. (Brazel & Rosen 2012) Thermoplastics are used in packaging and structural parts such as beverage bottles and covers of electrical devices.

Thermoset polymers can be moulded only once. When thermosets are heated for the first time, curing reaction forms covalent bonds between polymer chains and causes a cross-linked structure. More energy is needed to break covalent bonds than hydrogen bonds. Covalent bonds do not allow polymer to flow at high temperatures. Therefore thermosets degrade if they are reheated to the point where they could soften. Important thermoset polymers are thermoset polyesters, epoxies and phenolic resins. (Brazel & Rosen 2012)

Thermoplastics are also divided based on their mechanical and physical properties and crystal structure (Seppälä 2005). Thermoplastics are commonly presented in triangles like in Figure 2. Triangles also show the relative production volumes of the plastics. Commodity polymers are produced in larger quantities than engineering polymers. Engineering polymers are produced more than high performance polymers. The triangle on the right illustrates how bio-based polymers are located in relation to petroleum-based polymers. Most of the bio-based polymers in Figure 2 share the mechanical and physical properties of their petroleum-based counterparts.

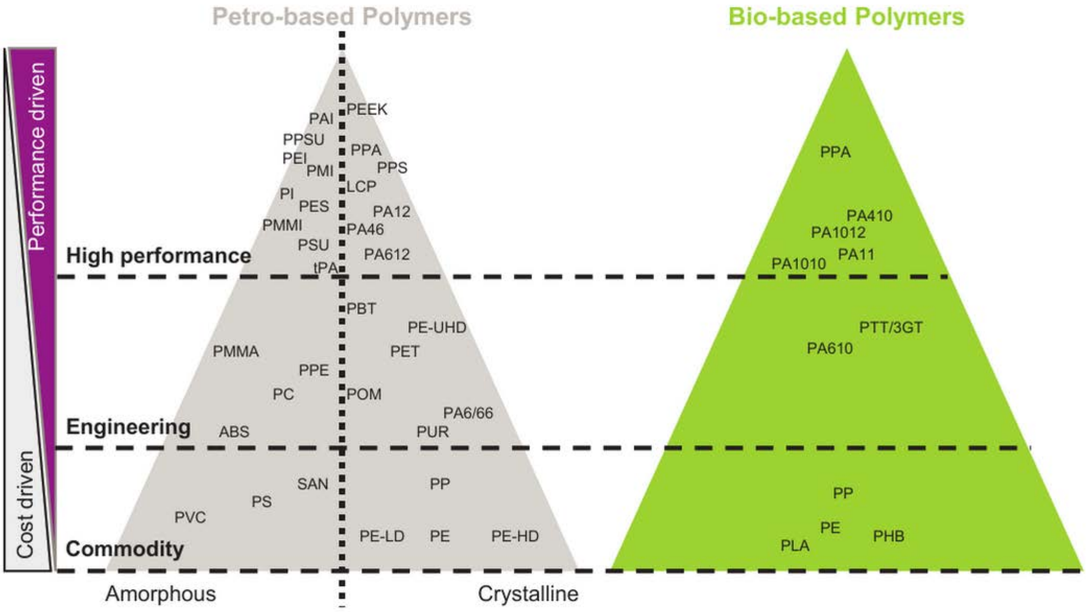

Figure 2. Classification of petroleum-based and bio-based polymers based on their crystal structure and properties. (Kabasci & Stevens 2013)

At the bottom are the most used commodity polymers such as polyvinylchloride (PVC), polyethylene (PE), and polypropylene (PP). Engineering polymers such as PC and PET are located in the middle and they provide better mechanical properties than commodity polymers. Engineering polymers can be used in various applications such as in transportation, machine parts and in covers of electrical devices. (Seppälä 2005)

At the top are the high performance plastics which are used in very demanding applications. High performance plastics are expensive and produced in small quantities, but they provide unique thermal and mechanical properties. For example, glass filled polyether ether ketone (PEEK) has a deflection temperature of over 300 °C, whereas the deflection temperature of PC is 130 - 140 °C. (Brydson 1999)

Plastics can have a crystalline or amorphous structure and the degree of crystallinity can be controlled during the manufacturing of plastics. Crystalline plastics, such as (PA), (PE) and (PP) are harder and provide better mechanical properties and chemical resistance than amorphous plastics. (Brazel & Rosen 2012) Amorphous plastics like PC and polymethyl methacrylate (PMMA) are transparent, and they are used in windows, transparent roofing and food containers (Brydson 1999).

2.2 Additives of plastics

The properties of plastics are controlled with additives and fillers. Plastics usually contain one or several additives, which are used to improve mechanical properties, enhance flame and weathering resistance or ease processing. Colouring additives and dyes are added to produce coloured plastics and fillers are used to, for example, increase molecular weight, or lower material costs. (Brazel & Rosen 2012) Additive content is normally a few percent (Silvennoinen 2014).

Plastics are reinforced, for example, with glass, carbon and aramid (Kevlar) fibres. Bio-based fibres, such as flax, are also used (Kuciel 2012). The fibre content of thermoplastics may be over 50 %. Reinforced plastics require also coupling agents which improve the adhesion between fibres and plastics matrix. Common coupling agents are silane and titanate. The reinforcing of plastics improves stiffness, strength and mechanical performance at high temperatures. Reinforcing affects the processability of plastics. Surface quality is reduced, but the dimensional stability is increased due to reduced moulding shrinkage. (Brazel & Rosen 2012) Reinforced plastics may increase tool wear and moulds may require more maintenance, if reinforced materials are constantly processed. The overall difference to the moulding of non-reinforced materials is difficult to estimate (Kämäräinen 2014).

Flame resistance is achieved with flame retardants. Flame spreading is slowed down by quenching flame propagation reactions, forming char or water, which inhibits burning and absorbs energy. Examples of flame retardants are tetrabromobisphenol-A, tetraphthalic andhydride, organic phosphates and hydrated alumina. Due to safety concerns, halogenated and bromine flame retardants are restricted, for example, in Nokia products (Nokia Networks 2014b).

Stabilizers, such as phenyl salicylate, 2-(2-hydroxyphenyl)-benzotriale, prevent degradation of plastics by ultraviolet (UV) radiation or high temperatures. Stabilizers prevent UV degradation by converting the electronic energy into heat (Brydson 1999). Some additives, like carbon black, behave as stabilizer and pigment. Carbon black absorbs UV radiation and prevents it from penetrating the surface of the material. (Brazel & Rosen 2012)

2.3 Production of plastics

Plastics are manufactured from natural or synthesized polymers. Raw materials for plastics are derived from fossil fuels or renewable resources such as starch, cellulose or soy. In the beginning of the 20th century, most plastics were made from renewable resources. Currently widely used plastics such as PA, PE, PVC, and PMMA were created in the 1920s and 1930s when crude oil became available in large quantities and at a reasonable price. Bio-based plastics like polylactic acid (PLA) and polyhydoxy-alkanoates (PHA) were created at the same time. However, large scale production of bio-based plastics started decades later in the 1990s. (Kabasci & Stevens 2013)

Natural gas, coal and crude oil are used for the production of petroleum-based plastics. Monomers such as propylene and ethylene are side products of oil refining. New sources for petroleum-based plastics are also utilized. The increased extraction of shale gas in the USA provides more raw materials for plastics production. Large scale shale gas production also keeps the price of gas low, which increases the production of petroleum-based polyolefins such as PE and PP (Sherman 2013).

Fossil fuels and derivatives from renewable resources need to be refined and processed several times before the final polymerization step. These processes can contain hazardous chemicals like phosgenes, chlorine and bis-phenol A (BPA). The extraction and refining of oil requires a lot of energy. It is assumed that oil extraction and refining requires 95 % of the energy needed to produce 1 kg of polymers (Maris et al. 2014).

Even though plastics are mainly made of petroleum-based raw materials, they can be used to reduce the life cycle emissions of the products. Plastics can provide lightweight solutions for transportation, which yields reductions in fuel consumption. Being lightweight is beneficial for other products as well, as transporting them requires less energy. However, plastics may not be the best materials for every application. The whole life cycle of the product must be studied to understand whether metals, plastics or ceramics provide the best alternative from an environmental and functional point of view.

3 LIFE CYCLE AND END-OF-LIFE

The life cycle of a product consists of the production of raw materials, the production of components and parts, manufacturing of the end product and transportation, installation, use and disposal. Life cycle of material is illustrated in Figure 3. The whole life cycle should be considered already at the designing stage of the product. During designing there are opportunities to effectively affect the environmental performance of the product (Lanoë et al. 2013). Without fully understanding the life cycle, improvements in one process can lead to worsening in the others.

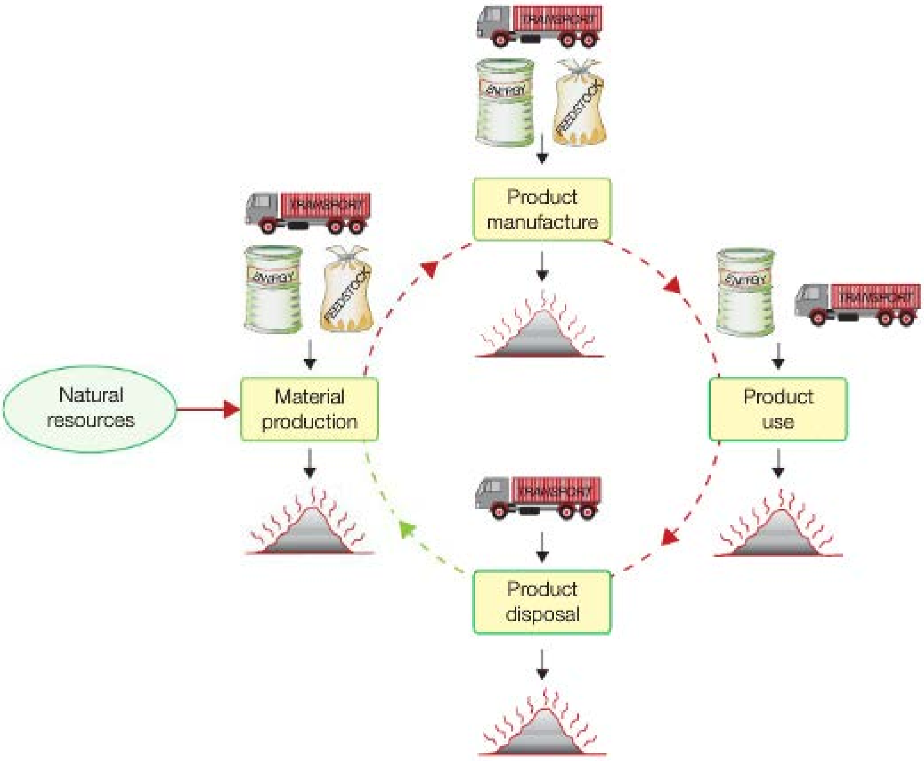

Figure 3. Life cycle of material from natural resources to disposal. (Ashby 2013)

Every process presented in Figure 3 requires energy, raw materials and produces emissions. Some of the energy and materials can be recovered after the disposal of the product. Possible disposal options for a product are landfill, combustion, recycling, re-engineering and re-use (Ashby 2013). Another important method to avoid of creating waste is to reduce material usage by improving design, for example. Worrel and Reuter (2014) presented waste treatment methods in hierarchical order:

1. reduce and avoid waste
2. reuse the product
3. recycle
4. recover energy
5. landfill.

Reducing and avoiding the waste is the preferred method, since energy is not required to process the waste. Re-engineering and re-use is suitable for some applications. Some products, like aircrafts, can be reused after replacing critical parts. Recycling means that the material from the old product is used to produce new items. Recycling reduces the use of virgin material. Recycling requires energy and produces emissions, but the energy is generally smaller than the energy required to produce virgin material. (Ashby 2013)

Recycled or secondary material can be used to substitute primary material or it can be used to produce different products. Term “down cycling” is also used, when recycled material is used to produce lower grade products (Lighart & Ansems 2012). For example, glass fibres from plastics are used for road construction.

Combustion for energy recovery is used to produce energy from old materials. All materials cannot be combusted and they must be separated from the waste stream. Landfill is the least favourable method, since none of the value of the product is recovered. Plastic waste treatment in the European Union, Switzerland and Norway is showed in Figure 4. In countries where landfilling is banned, most of the plastic waste is combusted. In many countries, the majority of waste is still delivered into landfills.

Figure 4. Plastic waste treatment in European Union, Switzerland and Norway. Energy recovery is generally more common than recycling. In some countries, the majority of waste is still delivered into landfills. (PlasticsEurope 2013)

4 LIFE CYCLE ASSESSMENT METHOD

Life cycle Assessment (LCA) is a standardized method which is used to evaluate environmental impacts during a product’s life cycle. First LCAs were conducted during the late 1960’s and they were concentrated mainly on energy and raw material usage (O’Neill 2003). Nowadays LCA contains also emission and impact analysis. In addition to global warming potentials, acidification and other environmental factors, economic and social impacts can be considered (Guinée et al. 2011). Currently, ISO standards 14040 and 14044 describe the general guidelines for LCA (SFS-EN ISO 14040, 14044 2006). These standards are not binding in anyway (Ashby 2013) and therefore assessments can contain large variations due to assumptions and choices made by the assessor.

Industry specific instructions for LCA are currently designed or have already been published. For example, ETSI ES 203 199 V1.3.0 (2014) standard is specifically designed for information and communication technology (ICT) devices and networks and PAS 2050 (2011) is designed to assess life cycle greenhouse gases of goods and services. LCA can be used to distinguish in which part of the product life cycle causes greatest environmental impacts. LCA method is seen as one of the promising methods to evaluate environmental impacts of the product (Urban & Bakshi 2009) (WRAP 2010).

The life cycle of a product is presented as a series of unit processes which all have a specific function. Results of LCA are presented as potential effects. Results can only estimate real impacts since regional differences have a significant effect on impacts (Lighart & Ansems 2012). Different systems or products are usually compared in LCA, because analysing only one option may not reveal whether the impacts are high or low (Collado-Ruiz & Ostad-Ahmad-Ghorabi 2013). Comparing assessments made by different assessors is not straightforward. Assumptions and estimations can be different between studies, even though the same standards and guidelines have been followed (Guldbrandsson & Bergmark 2012). Comparison becomes more feasible if studies from the same practitioner are compared.

Standard LCA consists of 4 phases: goal and scope definition, inventory assessment, impact assessment and interpretation. The flow chart of an LCA process is presented in Figure 5. LCA is an iterative process, so all phases affect the other phases. For example, the definition and interpretation steps may need to be modified after more information is obtained.

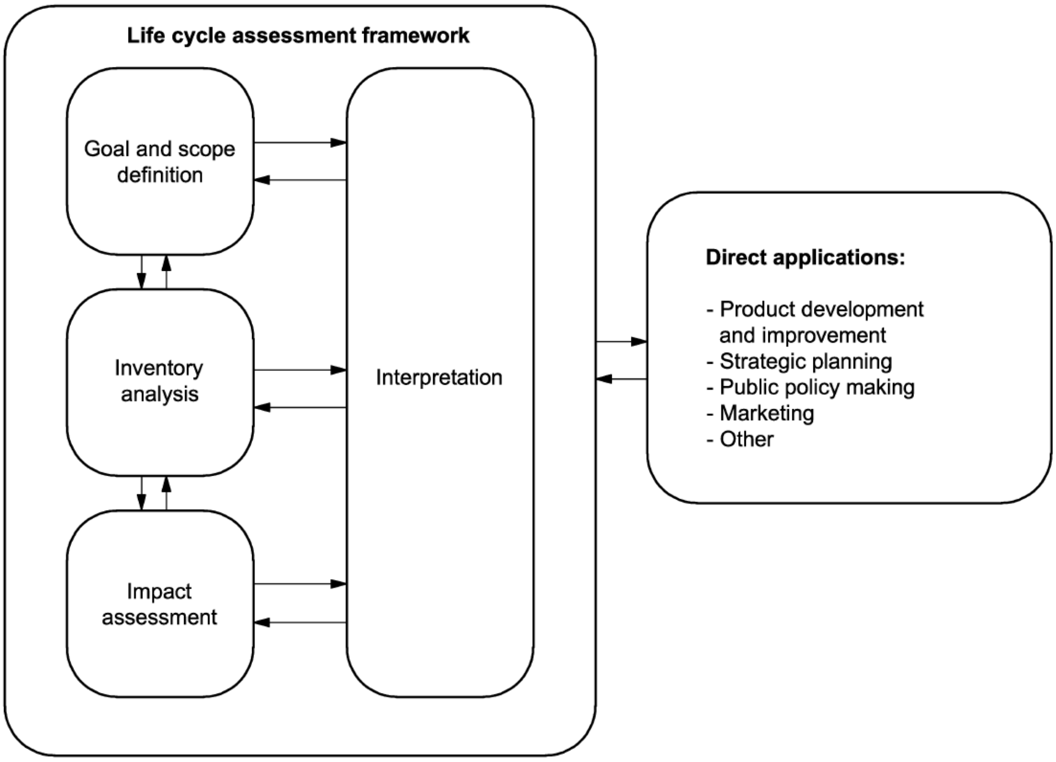

Figure 5. Framework of LCA according to ISO 14040 and 14044 standards. (SFS-EN ISO 14040 2006)

The purpose of the study is determined in the goal and scope definition phase. This phase also contains the selection of the system boundaries and functional unit. (SFS-EN ISO 14044 2006) Input and output data for processes are normalized to functional unit which is used to compare different systems. A functional unit can be a product or service; for example 1 kg of produced raw material or 1 GB of transferred data.

The system boundary defines which processes are taken into account in the study. The quality of the data determines whether processes must be added or removed from the system. The system boundary can be modified and refined during the study. Regional differences in data cause significant changes to results. Global average data may not reflect the local process conditions well, and site specific data may not provide comprehensive results of the environmental impacts. Significance of the assumptions is evaluated with the sensitivity analysis. (SFS-EN ISO 14044 2006)

Inventory analysis contains a collection of inputs and outputs from unit processes. Data is collected to Life Cycle Inventory (LCI). In a Life Cycle Impact Assessment (LCIA), the inventory data is classified to the selected impact categories such as acidification or climate change. LCIA also contains the calculation of category indicator results. For example, the category indicator for climate change is kg of CO_2-equivalents (kg $CO_{2,eq}$) per functional unit. The category indicators are used to evaluate the effect of emissions on category endpoint. (ISO 14044 2006) Category endpoint of climate change includes malnutrition, decreasing bio diversity and flooding (European Commission 2010).

LCA can be performed as a Cradle to Grave or Cradle to Gate assessment. A Cradle to Grave assessment contains the life cycle phases from material extraction to final disposal. A Cradle to Gate assessment contains life cycle steps before use phase. Cradle to Gate assessments are also used to study only material production when it is not known which product the material will be used in. Omitting the use phase is also viable when comparing different materials if the use phase is similar for all options. Cradle to Gate assessments can contain the end-of-life phase, if it is known how the material will be treated after its useful life. Figure 6 illustrates different assessment types.

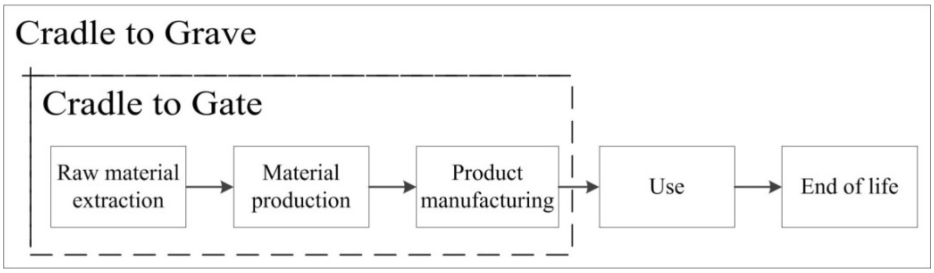

Figure 6. An example of LCA system boundaries. Cradle to Grave assessment considers the whole life cycle. Cradle to Gate assessment considers the production of the product or the study can be limited only to material production.

Even though LCA according to ISO standards is found to be a reliable tool, some flaws and inaccuracies are reported and discussed. Some of the criticism is targeted at specific cases, like LCAs in aluminium industry, or to the whole LCA procedure. For example, the use of industry-wide data may not give a realistic picture for specific cases. All manufacturing methods may not be included and the data can be old. In addition, the use of functional unit may hinder perception of how environmental impacts are evolved in reality. For example, environmental impacts of a product can be decreased according to functional unit in LCA but the increase of the overall production increases combined impacts. (Gang & Müller 2012)

4.1 Impact categories

The environmental impact categories in this study are climate change and primary energy demand of the raw material production. Several other impact categories exist (Lighart & Ansems 2012). In the report from Waste & Resources Action Programme (WRAP 2010) it was stated that studies should also consider other impact categories than climate change and primary energy demand. Use of simple indicators may not give information of toxic materials or materials depletion (van der Velden 2013). However, climate change is a widely used and understood category. The selection of impact categories is also affected by the purpose of the study. For example, customers may require that a company must provide a carbon footprint calculation of the products. Many stakeholders are also focused on climate change and size of carbon footprint (Guldbrandsson & Bergmark 2012).

4.1.1 Primary energy demand

Primary energy demand contains energy derived from fossil fuels and non-fossil fuels. Primary energy is the energy which is embodied in the natural resources such as coal, natural gas, bio-energy and uranium. Primary energy needs to be converted into usable energy. (IPCC 2014) The primary energy demand for lighting is presented in Figure 7. According to the illustration, 320 units of primary energy are required to produce 1 unit of lighting energy.

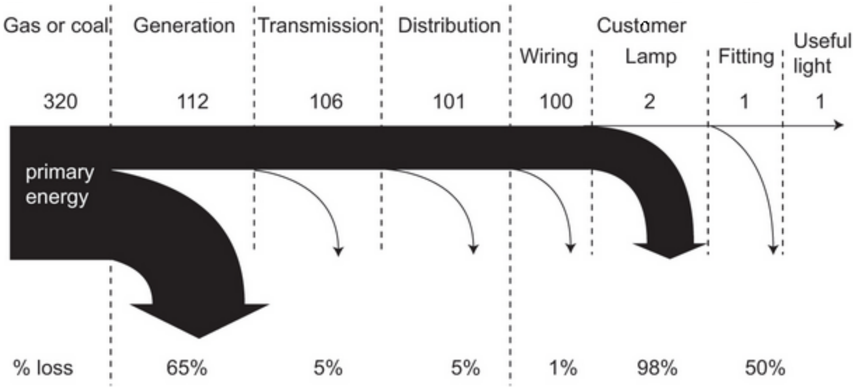

Figure 7. Illustration of primary energy demand for one unit of light energy. Primary energy is derived from natural resources and transformed into useful energy. (IPCC 2007)

Some studies and reports concentrate only on non-renewable energy usage (NREU) or fossil fuel depletion (Shen et al. 2011) (DuPont 2014a) (Vercalsteren et al. 2010) (Papong et al. 2014). Comparisons of NREU of bio-based and petroleum-based materials are used to illustrate that bio-based materials required less fossil fuels. Total energy consumption of bio-based materials may be higher than that of petroleum-based materials. This study compares partly bio-based materials with fully petroleum-based materials. For viable comparison, energy derived from fossil fuels and non-fossil fuels is considered.

4.1.2 Climate change

Climate change is related to GHG emissions, which increase atmospheric temperature. Climate change also causes changes in ocean fluxes and sea level. More specific details about climate change are found from in a report of Intergovernmental Panel on Climate Change (IPCC) (2013).

Climate impacts of GHG emissions are evaluated with global warming potential (GWP). GWPs are used, for example, in the Kyoto Protocol. The Kyoto Protocol is an international agreement under United Nations aimed to set international binding emissions reduction targets (United Nations 1998). GWP compares time-integrated radiative forcing of GHG to radiative forcing of carbon dioxide (CO_2). GWP is calculated with the equation:

$$GWP = \frac{\int_0^{TH} k_{GHG} y_{GHG}(t)dt}{\int_0^{TH} k_{CO_2} y_{CO_2}(t)dt} \tag{1}$$

where k_{GHG} and k_{CO2} are radiative forcing of GHG and CO_2, respectively and y_{GHG} and y_{CO2} are lifetimes of GHG and CO_2, respectively. Life time y is expressed as a CO_2 impulse response functions. (Guest et al. 2013) Each greenhouse gas has its own GWP.

CO_2, methane, ozone and nitrous oxide are important and commonly reported GHGs. The major greenhouse gas in the atmosphere is water vapour. The quantity of water vapour is controlled mostly by air temperature, and water vapour has a negligible effect on climate change. (IPCC 2013)

GWP results for a product are presented as CO_2-equivalent ($CO_{2,eq}$) emissions for different time horizons. The most used time horizon is 100 years which is expressed as GWP 100. There is no scientific argument for favouring the 100 year time horizon (IPCC 2013). Vogtländer et al. (2014) suggested that it was a political decision to balance the short-term effect of methane and the long-term effect of chlorofluorocarbons (CFC). Because GHGs have different lifetimes in the atmosphere, the choice of the time horizon has an effect on GWP. The use of a short time horizon 20 years, for example, increases the importance of short-lived GHGs like methane. A longer time horizon increases the importance of long-lived GHGs such as CO_2, CFCs and N_2O. (Brandao 2013)

Table 1 shows GWP for greenhouse gases that shall be reported in GHG inventories according to Greenhouse Gas Protocol (2013). Values show what the effect of time horizon is. Because methane is a short-lived GHG, its GWP is larger in a 20 year time horizon than in a 100 year time horizon. CO_2 and nitrous oxide have a similar life time and therefore their GWPs remain constant.

Table 1. GWPs of various greenhouse gases according to IPCC (2013). Values from (IPCC 2007) are shown for comparison. Greenhouse Gas Protocol (2013) requires these gases to be reported in GHG inventories.

GHG	**Chemical formula**	**GWP 20**	**GWP 100**	**GWP 100 (2007)**
Carbon dioxide	CO_2	1	1	1
Methane	CH_4	84	28	25
Nitrous dioxide	N_2O	264	265	298
Hydrochlorofluorocarbons (HCFC), e.g. HCFC-22	$CHClF_2$	5 280	1 760	1810
Perfluorocarbons (PFC), e.g. PFC-14	CF_4	4480	6630	7390
Sulphur hexafluoride	SF_6	17 500	23 500	22 800
Nitrogen trifluoride	NF_3	12 800	16 100	17 200

GWP values for gases have changed over time. Better calculation methods provide more realistic estimations for GWPs. Different values make the comparing of studies difficult although GWP of most common GHGs are not changed significantly. IPCC gives updated reports and GWPs every few years.

4.2 Recycling in LCA

ISO 14040 and 14044 define two procedures to treat recycling in LCA. If no changes occur in the inherent properties of recycled material and the recycled material is reused for similar application, a closed-loop product system is applied. If recycled material is used in other product systems or properties of the material are changed from virgin material, an open-loop product system is preferred. (SFS-EN ISO 14044 2006)

An example of a closed-loop product system is the use of recycled plastic bottles to manufacture new bottles. Using recycled plastic bottles to produce plastics covers is an example of an open-loop product system. Lighart and Ansems (2012) define also a model of semi-open loop recycling, in which the inherent properties of the material are not changed, but the recycled material is used for another product. Defining the correct material flows for LCA can be difficult if recycled material is derived from various sources. In the closed-loop recycling, the choices are easy, but closed-loop recycling rarely exists in reality. (Lighart & Ansems 2012)

Recycling has been studied in several LCAs. Reports from British Waste & Resources Action Programme analysed in total over 80 LCAs which were focused on recycling methods (WRAP 2010). The recycling of PET bottles was investigated by Shen et al. (2011). They compared the environmental impacts of virgin PET bottles with PET bottles made partly from recycled material.

Modelling the recycling of products that have a long useful lifetime is challenging, because recycling and waste treatment methods have probably evolved significantly after the LCA study (Sandin et al. 2014). That is especially the case in the construction industry, but it can also concern base stations, which may have a lifetime of ten years. The LCA can only indicate possible impacts caused in end-of-life phase due to uncertainty of future technology (Guldbrandsson & Bergmark 2012).

One key issue regarding recycling studies is how to allocate inputs and outputs. It must be considered, whether the environmental impacts are targeted at virgin or recycled material. Allocation is also performed when recycled material is used for several applications. For example, a recycled PET pellet can be used for fibre and bottle production (Shen et al. 2011). The allocation of the impacts of recycled material is discussed in several publications (Gang & Müller 2012) (Lighart & Ansems 2012) (Sandin et al. 2014). ISO 14044 standard prefers that no allocation is performed. Processes should be divided into sub-processes or the system should be expanded. If allocation is needed, it should be based on physical properties of material flows, for example mass. Other properties, such as economic value can be used for allocation if physical relationships cannot be used. (SFS-EN ISO 14044 2006) However, Ardente and Cellura (2012) suggest that the allocation method should be selected on a case-by-case basis. An assessment can combine several allocation approaches as in the study by Shen et al. (2010).

Common allocation methods for the recycling point of view are described in the following chapters. The system expansion is also presented, although it is not an allocation method as such. Allocation methods are roughly classified into two approaches: cut-off approach and end-of-life recycling. Methods similar to the cut-off approach assume that the impacts are clearly divided between different life cycles. The principle of the division varies between methods. These methods include cut-off approach, economic allocation and 50:50 method.

In methods similar to the end-of-life recycling, it is assumed that the virgin material is substituted by recycled material derived from the studied product. In other words, the recycled material in end-of-life recycling comes within the system boundary. In the cut-off approach the recycled material is derived from outside the system boundary. Methods, which are similar to the end-of-life recycling, are value-corrected substitution and multiple recycling method.

4.2.1 Cut-off approach

Cut-off approach is the most common allocation method. The cut-off approach is also known as recycled content allocation (Johnson et al. 2013) or input oriented allocation (Lighart & Ansems 2012). The impacts directly caused by the product are considered in the life cycle. The disposal and waste treatment are allocated to the first life of the product and recycling processes and the use of recycled materials are considered in the second life. Recycled material used for the product is assumed to replace virgin material in the system (Lighart & Ansems 2012) (Sandin et al. 2014). The cut-off approach is presented in Figure 8. Due to its simple approach, the cut-off approach is applied in the LCA in this study.

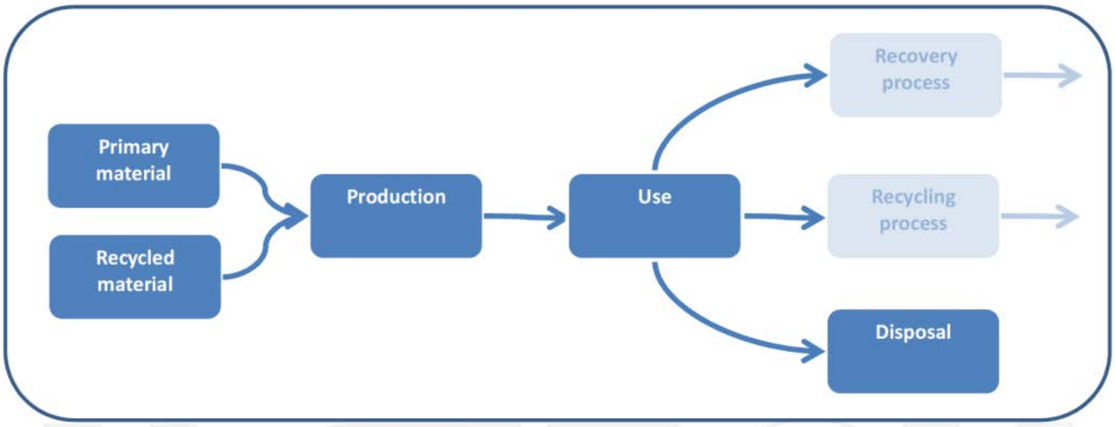

Figure 8. The principle of cut-off approach. Recycling of the product is not included in the life cycle. (Lighart & Ansems 2012)

The advantages of the cut-off approach are its simplicity and the ease of understanding. The method simplifies the LCA study in which recycled material is used, since it may not be known how many times the specific batch of recycled material has been reprocessed. The cut-off approach also promotes the use of recycled material because the production of recycled materials causes generally lower environmental impacts than the production of virgin materials.

However, the cut-off approach does not support designing recyclable products, since the recycling of the product does not reduce environmental impacts in the first life of the material (Gediga 2014). Johnson et al. (2013) point out that the cut-off approach may not effectively consider the situation in which more recycled material is used in the manufacturing phase than is recovered in the end-of-life phase. This situation requires the use of recycled material from outside the system boundary. (Johnson et al. 2013) This can be relevant in the case of plastic parts, if recycled material is used in the product and the material is incinerated after use. In this scenario, waste from different plastic parts is needed to support the production of the studied part. According to the cut-off approach, the impacts from the products, which are used as recycled materials, are not considered. The cut-off approach may therefore favour the use of recycled materials, which are derived from products with high environmental impacts.

4.2.2 Economic allocation

Economic allocation is used to combine economic systems and product systems. Environmental impacts for multiple products are divided based on their economic values. In the case of recycling, the impacts from the collection and dismantling processes are divided between virgin and recycled materials. If used virgin material yields 100 € and the processed scrap yields 150 € for the collection and dismantling, the total yield is 250 €. By using economic allocation, 40 % or the environmental impacts of the scrap processing is allocated to the virgin material and 60 % to the recycled material. The example is illustrated in Figure 9.

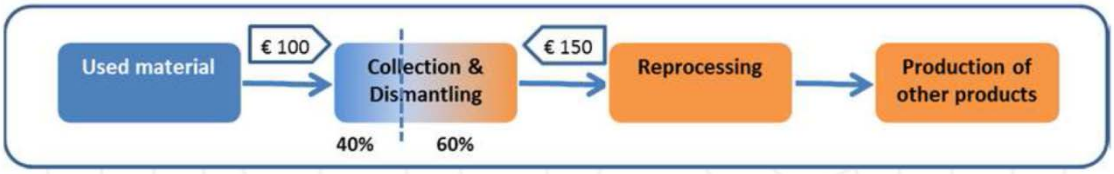

Figure 9. The principle of economic allocation in recycling. Environmental impacts from the collection and dismantling processes are divided between first and second life based on the economic values of virgin and recycled materials. (Lighart & Ansems 2012)

Economic allocation can be used when a process has multiple output products. A problem with economic allocation is that the prices and price ratios of co-products differ over time. Although, it is stated that allocation based on physical relationships may also have fluctuations. Especially in the food industry, product flows can differ depending on the year. (Ardente & Cellura 2012) Regulations and fees make the estimation of the the prices difficult (Lighart & Ansems 2012).

4.2.3 50:50 method

The environmental impacts of primary material production and recycling processes are divided between the first and second life in the 50:50 method (Johnson et al. 2013). According to this method recycling is beneficial, if its environmental burdens are less than those of the virgin material production and final waste treatment (Nicholson et al. 2009).

4.2.4 *End-of-life recycling*

The end-of-life recycling method assumes that recycled material from the studied product substitutes virgin material at the beginning of the life cycle. If the material is reutilized by incineration with energy recovery, the produced heat substitutes the heat from other fuels (Sandin et al. 2014).

End-of-life recycling is also known as the avoided burden approach (Gediga 2014) or output oriented allocation (Lighart & Ansems 2012). It can be applied to closed loop or semi-closed loop recycling. It is the opposite of cut-off approach, in which the first life of the recycled material is not considered. The end-of-life recycling method is presented in Figure 10. Emission factors are used in the end-of-life recycling method to consider that emissions of the are released in the future. The use of emission factors to describe future emissions adds uncertainty to the assessment. (Johnson et al. 2013)

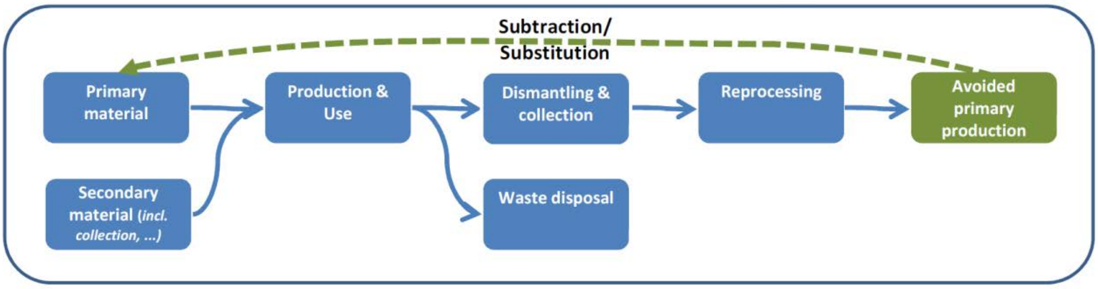

Figure 10. End-of-life recycling method. The recycling of used materials substitutes primary material. (Lighart & Ansems 2012)

Johnson et al. (2013) observed in their study that the impacts were significantly higher when the end-of-life recycling method was applied instead of cut-off approach. The end-of-life approach may promote the use of virgin materials, if their recycling potential is overestimated (Gediga 2014). However, end-of-life recycling supports designing recyclable products, since a high recovery rate reduces the environmental impacts of the product.

4.2.5 *Value-corrected substitution*

In value-corrected substitution it is assumed that the virgin and recycled materials have different inherent properties. Changes of inherent properties are indicated with ratio in prices between the virgin and recycled materials. As in the end-of-life recycling, recycled material is used to substitute virgin material. For example, if 80 kg material is recycled and the material has 90 % of the value of virgin material, 72 kg of virgin material is substituted with recycled material. (Lighart & Ansems 2012)

Johnson et al. (2013) studied value corrected substitution method of aluminium recycling, and stated that the method contains defects. In the case of aluminium, the method cannot consider changes in the ratio of the prices of virgin and recycled aluminium. Johnson et al. (2013) suggest that the method works if the price ratios of specific material or alloy are stable. Price fluctuations of the materials can increase or decrease environmental burdens even though physical characteristics of the material or system remain the same (Lighart & Ansems 2012).

4.2.6 Multiple recycling method

The International Iron and Steel Institute developed a multiple recycling method. The method takes into consideration that the impacts of the virgin material affect the impacts of the recycled material. As material is recycled repeatedly, environmental impacts are reduced and eventually stabilized. An example of the multiple recycling approach is seen in Figure 11. The method can be used for a material whose inherent properties are not significantly changed in recycling. (Lighart & Ansems 2012)

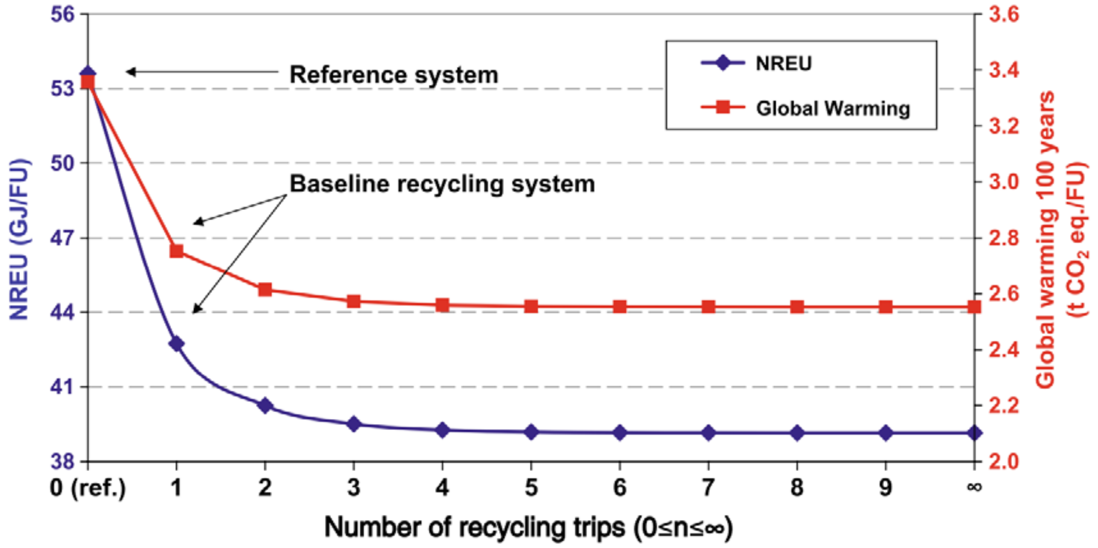

Figure 11. Multiple recycling method applied to PET bottle recycling. Non-renewable energy usage (NREU) and global warming potential are stabilized after 3 recycling trips. (Shen et al. 2011)

4.2.7 System expansion

In ISO 14044 standard, system expansion is preferred instead of allocation. The boundaries of the system are expanded so that the system is considered to be closed. Expanding the system too much increases the workload and increases uncertainty (Lighart & Ansems 2012). New allocation issues may also arise, when new processes are taken into account (Tsiropolous et al. 2013).

System expansion was used in the study of PET bottle recycling by Shen et al. (2011). In that study, system boundaries were expanded to take the virgin material production into account, which was needed to achieve the function unit. System expansion was used in the study by Shen et al. (2010). Their study suggests that system expansion is the most favourable allocation method for open-loop recycling systems.

4.3 Bio-based materials in LCA

Bio-based materials contain biogenic carbon. The default assumption is to consider biogenic carbon as an emission. For example, if 1 t carbon is extracted from biomass resource poll, such as forest, 3.67 t CO_2 is emitted to atmosphere in the year of extraction (Guest et al. 2013). In other words, the extracted biogenic carbon is assumed to be an emission regardless of the product lifetime. According to Vogtländer et al. (2014), many LCA practitioners are decided not to consider biogenic CO_2 emissions. It is reasoned, that the CO_2 captured by biomass is eventually returned to atmosphere. Therefore net change in CO_2 emissions does not occur.

In some cases biogenic carbon is assumed to be stored in a product for a period of time. For example, the industry of bio-based products suggests that biogenic carbon storage should be credited in carbon footprint calculations (Vogtländer et al. 2014). The stored carbon is released back to the atmosphere during the life cycle of the product, for example during incineration. Carbon neutrality is claimed, when the growth of biomass for the application sequesters equal or more CO_2 than is released during the production, use and disposal of the application (Brandao et al. 2013).

Different methods for treating biogenic carbon are presented in ISO/TS 14067, GHG Protocol, PAS 2050 and Climate Declaration. All these methods are based on ISO 14040 and 14044 standards, but they include different requirements and guidelines. (Garcia & Freire 2014) The technical specification ISO/TS 14067 defines how to evaluate the carbon footprint of a product. In ISO/TS 14067 biogenic carbon storage is not calculated in the carbon footprint, but it is reported separately (ISO/TS 14067 2013). ISO/TS 14067 does not provide a method to calculate delayed emission from long lived products such as wood furniture (Garcia & Freire 2014).

Biogenic carbon storage is included in carbon footprints according to GHG Protocol and Publicly Available Specification (PAS 2050 2011). GHG Protocol is based on a former PAS 2050 specification. Both methods contain similar guidelines, but PAS 2050 does not include biogenic carbon of food and feed in calculations due to their short life cycle. Carbon emissions and removals from food and feed cancel each other out. (PAS 2050 2011) PAS 2050 recommends the use of sector specific rules for the calculation (Garcia & Freire 2014). The approach of this study is based on GHG Protocol. GHG Protocol is used in many studies, so comparing this and other studies is easier, although not straightforward.

The Climate Declaration method is created by International Environmental Product Declaration (EPD) Systems and concentrates only on GHG emissions. Current Climate Declaration follows the same principles as PAS 2050:2011. For example, biogenic emissions from food and feed are excluded. The older 2008 Climate Declaration did not take biogenic carbon into account. (EPD 2014) (Garcia & Freire 2014)

Garcia and Freire (2014) made a comparison between CF calculation methods to point out the differences, how biogenic carbon is considered. They assessed the CF of particle board production according to the ISO/TS 14067, GHG Protocol, PAS 2050 and old

Climate Declaration 2008. Cradle to Gate CF is shown in Figure 12. The results were somewhat conflicting. The use of GHG Protocol and PAS 2050 results in a negative carbon footprint. Carbon footprints, according to Climate Declaration and ISO/TS 14067, are positive. Clearly, the choice of assessment method affects the results greatly.

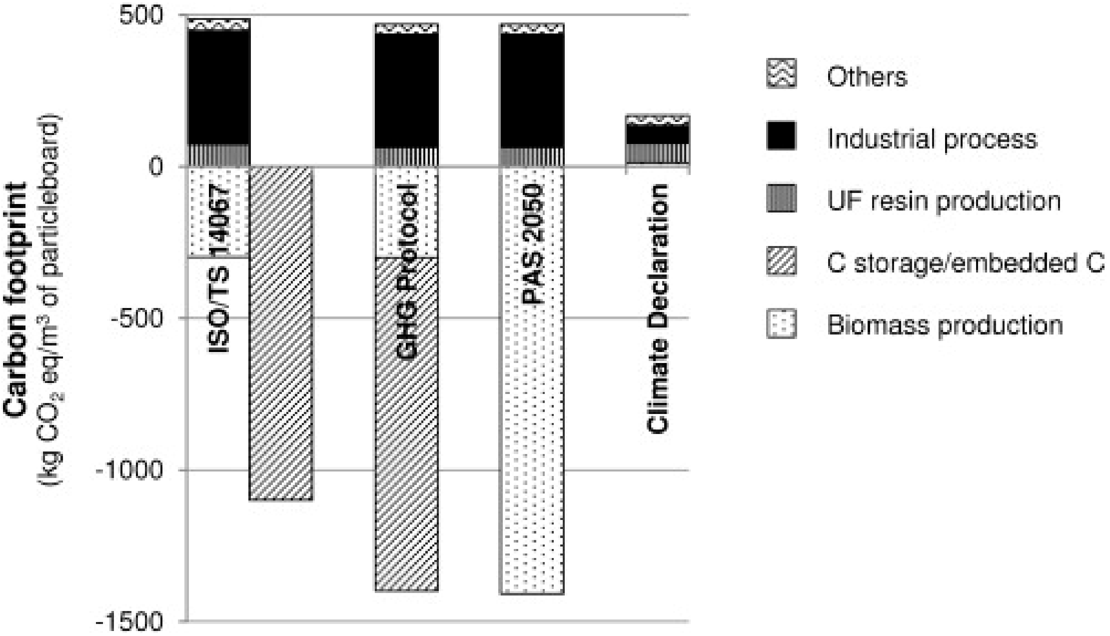

Figure 12. Comparison of different methodologies to treat biogenic carbon in Cradle to Gate type of LCA. GHG protocol and PAS 2050 methods result in negative carbon footprints and ISO/TS 10467 and Climate Declaration result in positive carbon footprints. Carbon storage is reported separately according to ISO/TS 14067. (Garcia & Freire 2014)

5 RECYCLING OF PLASTICS

It is estimated that the plastics industry has grown 8.7 % every year starting from 1950. The annual production of plastics in 2012 was 288 million tonnes, of which 57 million tonnes were produced in Europe. At the same time, more and more plastic waste is produced and reutilization of the waste has become an important business. According to PlasticsEurope, the association of European plastics manufacturers, 61.9 % of plastic waste is either recycled or used for energy production in the European Union (EU), Norway and Switzerland. The remaining 38.1 % is disposed of as landfill. 25.2 million tonnes of plastics ended up in the waste stream in 2012, and 62.2 % of the waste is derived from packaging. (PlasticsEurope 2013) It is estimated that 4 % of municipal waste in Europe comes from electronic equipment (Georgiadis & Besiou 2010). Electronic devices contain large amounts of plastic parts such as insulators and covers. Currently, electronic waste is one of the fastest growing waste streams (Deeptimayee et al. 2012).

Recycling of plastics has already been successfully applied to many commodity plastics and plastics have been recycled since the 1970s. Materials like polyvinyl chloride (PVC), PP and PET are widely recycled. Engineering thermoplastics are not recycled as efficiently. However, methods for recycling common engineering plastics such as PC and PA have been created decades ago. (Scheirs 1998) The problem with recycling engineering plastics is the identification of different plastic grades which may contain many additives or coatings (Arensman 2000).

Developments in recycling technology allow for more efficient recycling of materials (Hopewell et al. 2009). Before 1991 and the development of the super clean recycling technology, it was not possible to use recycled plastics in food applications due to contamination. (Welle 2011) Recycled plastics are needed to mix with virgin materials to meet the requirements for colouring and food safety (Shen et al. 2011). Novel recycling methods make it possible to recycle plastics from various sources.

The large variation of plastics grades makes recycling demanding. Plastics may contain different types of additives like pigments, flame retardants or UV-stabilizers. The identification of plastics is difficult, if their properties are close to each other. Some plastic products contain a recycling code, which makes the separation process easier. Currently, the recycling codes from 1 to 6 are available for 6 types of polymers:

1. PET
2. high density PE (HDPE)
3. vinyl polymers
4. low density PE (LDPE)
5. PP
6. polystyrene (PS).

All other plastics belong under code 7. (Brazel & Rosen 2012) However, some plastic products contain an additional marking, which indicates the material type. An example of a recycling code is shown in Figure 13.

Figure 13. Recycling mark in a plastics product. Number 07 indicates that the plastic belongs to group 'other'. Additional marking informs that the material is flame retarded (FR) polycarbonate (PC).

Recycled materials are used in new plastic products, blended with other materials or used as fibres in clothing. Plastic waste can also be incinerated to produce heat. The processing properties of plastics can be changed due to recycling. For example, molecular weight is typically reduced, which increases fluidity. (Strong 2006)

5.1 Advantages of plastics recycling

The recycling of plastics must provide advantages, and recycling just for its own sake is not enough (Khare 1999). An obvious benefit is that the use of recycled plastics decreases the need for crude oil. The production of recycled plastics can be more energy efficient and cause fewer emissions than the production of virgin plastics. (Shen et al. 2010) Arena et al. (2003) concluded that the recycling of PET can reduce GHG emissions almost by 90 %. PET recycling required 93 % less crude oil than the production of virgin PET. The study by Morris (2005) suggests that the recycling of plastics requires approximately 95 % less energy than the production of virgin plastics. Energy efficiency depends on the plastics grade, condition and recycling method. Pure plastic waste is easier to recycle than a contaminated mixture of different plastics. Mechanical recycling is more efficient than chemical recycling or biodegradation. (Hopewell et al. 2009)

A large amount of plastics waste is currently incinerated for energy production. According to Hopewell et al. (2009), the recycling of plastics saves more energy than is produced by incineration. A study by Hischier et al. (2005) concluded that recycling causes fewer emissions than the incineration of waste electric and electronic devices. The study by Morris (2005) compared the recycling of municipal waste with landfilling and incineration. According to the LCA model, the recycling caused lower environmental impacts than solid waste disposal or combustion, even if energy is recovered from landfill gases and combustion. Environmental impacts were evaluated, among other things, with energy usage, GHG emissions, eutrophication and acidification. All indicators suggested that the environmental burden of recycling is lower than that of landfilling or incineration. The same study proposes that the economic value for the pollution prevention caused by recycling outweighs the costs of recycling.

Tuomisaari (2014) stated that recycling is also cost-effective, if the waste sorting and logistics are well controlled. Sorting the waste at its place of origin eases further waste processing. Transporting the plastic waste is economical, if the waste is compressed into a small size. The price ratio between virgin and recycled material depends on the quality of the recyclate. If recycled material is required to have exactly the same properties as virgin material, the price of the recyclate is 70 - 80 % of the price of the virgin plastics.

5.2 Difficulties in plastics recycling

The collection and processing of plastic waste require several steps. The sorting of waste requires also manual work. Sorting must be efficient, since even a small amount of contaminant can ruin a large batch of recycled material. Especially PVC in a PET waste stream is difficult to distinguish, since the densities of PVC and PET are close to each other. (Scheirs 1998) The recycling of industrial waste is easier than the recycling of plastic products, since the plastics grade of the end product can be difficult to distinguish, especially if the material is marked with recycling code 7. Material grades in the industrial waste are usually well known. Recyclate derived from moulding scrap provides good quality material but improvements in the material efficiency of moulding reduce the availability of recyclable material. (Buckel 2014) (Rüdiger 2014) (Silvennoinen 2014) Moulding scrap is therefore an unstable source of material. A high recycled material content is difficult to achieve for high production volume products made of moulding scrap.

Recycling affects the properties of plastics. Mechanical and weathering properties are degraded if polymer chains are shortened significantly during recycling. Mixing of virgin and recycled material has also been found to degrade material properties. According to Rosato et al. (2000), a recycled material content of 25 - 30 % will result in degraded physical properties. However, commercial PC grades exist which contain 30 % of recycled material and have properties comparable to 100 % virgin PC (Bayer MaterialScience 2014).

The use of recycled material causes limitations to available colours. Most recycled materials are black or dark grey (Scheirs 1998). Dark colours are easy to achieve if the waste is derived from various products and the availability of specific plastics waste is unknown. This may be the case with engineering plastics, which are used in relatively small quantities with various colours and additives. To fulfil specific material requirements, such as flame resistance, material properties must be monitored and additives added, if necessary, during recycling. If flame retardant waste is available, flame resistance is maintained after recycling. For example, Statler et al (2008) observed that the flame resistance of PC can be retained after mechanical recycling.

5.3 Recycling methods

Mechanical recycling is the most used recycling method, but other methods such as chemical and thermochemical recycling (feedstock recycling) are also shortly described. Recycling methods may require similar scrap collection and pre-treatment processes. A summary of end-of-life options for plastics is shown in Figure 14. The figure shows at which point of plastics production the recycled material is used.

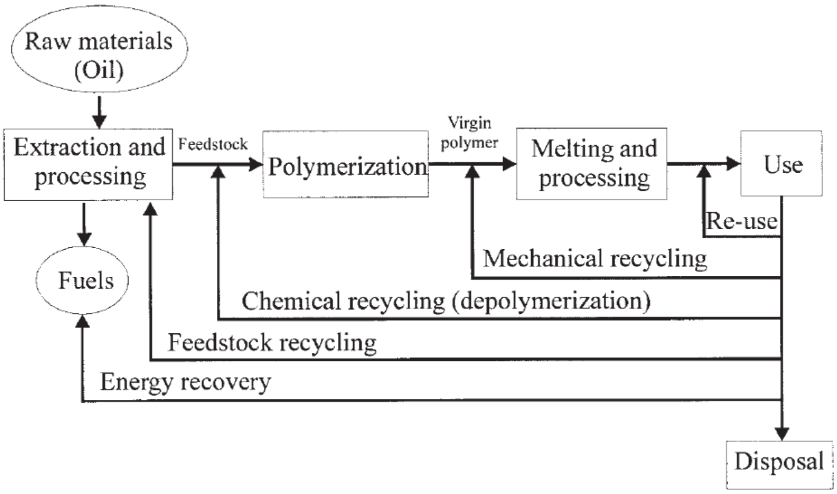

Figure 14. End-of-life treatment of plastics. (Perugini et al. 2005)

5.3.1 Mechanical recycling

In mechanical recycling, plastic products are shredded in pellets or flakes which are remoulded. Waste plastics must be carefully sorted prior to processing, because impurities in the waste can deteriorate material properties. (Tuomisaari 2014) Mechanical recycling is most suitable for industrial waste, since it contains less impurities and can be sorted more easily than consumer waste (Khare 1999). Mechanical recycling has been found to cause fewer emissions and require less energy than chemical recycling (Shen et al. 2010). The recycling process is performed with a single machine, if the plastic waste is well sorted and does not require additional cutting or shredding. Plastic parts smaller than 0.5 m x 0.5 m and lighter than 500 g are directly fed into the recycling machine. A recycling system from Erema is shown in Figure 15. Plastic waste is ground, melted, screened and granulated within one system. Dust and other impurities are removed from the plastics after granulating. The size of the granulate is approximately 4x4x5 mm. Recycled PP pellets are shown in Figure 16. Purified granulates are packed in 1000 kg sacks like in Figure 17. (Tuomisaari 2014)

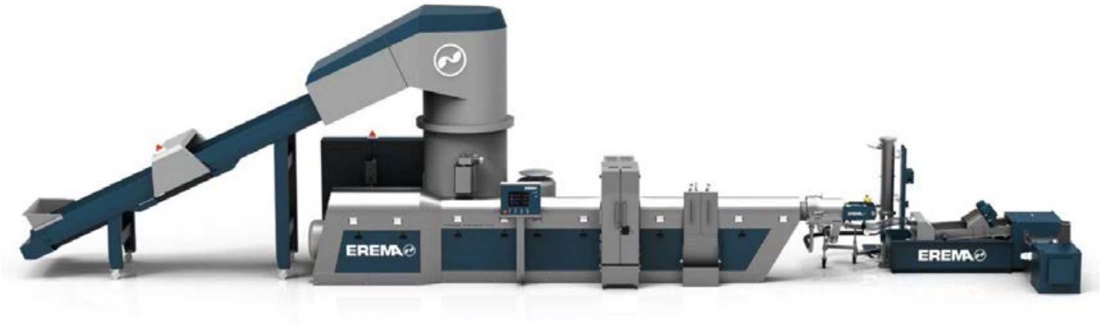

Figure 15. Erema recycling system, which is used to grind, melt, screen and granulate the plastics waste. The same system is used for various plastics. (Erema 2014)

Figure 16. Plastic waste is processed into small granulates with size of 4x4x5 mm. Granulates in the photo are PP.

Figure 17. Plastic granulates are poured from the silo into sacks. One sack contains 1000 kg recycled plastics.

Shear forces and processing temperatures have an effect on the properties of recycled material. High temperatures and shear forces during recycling may reduce impact strength and viscosity. Ground waste should be fine-grained because it is easier to melt than coarse resin. The quality of the recycled material is also affected by the recycling machine. The ground plastics waste is melted and mixed in the extruder. The longer the extruder, the lower shear forces are needed to melt the material. (Tuomisaari 2014) If the recycling process is well controlled, the resulting material has properties comparable to virgin plastics (Mahanta et al. 2012). Some additives such as antioxidants are degraded during recycling, but they can be added when the recycled material is moulded. Antioxidants are important in multicomponent moulding. (Tuomisaari 2014)

5.3.2 Chemical recycling

In chemical recycling, the polymer is decomposed to its starting monomers. Chemical recycling is performed by hydrolysis, glycolysis, hydroglycolysis, methanolysis or aminolysis. Processing of plastics chemically may require the use of toxic chemicals and the processing costs are much higher than those of mechanical recycling. (Antonakou & Achilias 2013) The reaction products are liquids and gases which can be toxic. Chemical recycling is effective for mixed plastics waste which is difficult to separate for mechanical recycling. (Strong 2006)

5.3.3 Thermochemical recycling

Thermochemical or feedstock recycling decomposes plastics to a condensed mixture. The process is carried out in high temperatures in the absence of air (pyrolysis), in the presence of hydrogen (hydrocracking) or in a controlled amount of oxygen (gasification) (Perugini et al. 2005). The mixture contains gaseous products like CO_2, CO and H_2 and liquid monomers. For example, thermochemical recycling of PC results in the aforementioned gaseous products and monomers like bis-phenol A. (Antonakou & Achilias 2013) Thermochemical recycling produces simpler chemical components than chemical recycling.

5.3.4 Biodegradation

Biodegradable materials are degraded by composting or by sun light, for instance. Biodegrading requires controlled conditions and does not easily occur in landfills. (Strong 2006) A backyard compost heap may not be effective for biodegradation therefore industrial scale composting facilities are required (Hottle et al. 2013). Biodegradation products can also be harmful to the environment. (Strong 2006)

Biodegradable plastics are mostly used in packaging, since their life cycle is short, and biodegradation helps to reduce the amount of waste ending up in the landfills. Biodegradability occurs due to the breaking of polymer chains and it is independent of the source of raw materials. For example, hydrolysis of the ester linkage causes degrading of PLA (Brazel & Rosen 2012). Biodegradable plastics can contain raw materials from biomass, but some fully petroleum-based plastics are also biodegradable, such as polycaprolactane (PCL) and polybutylene adipate terephthalate (PBAT). (Kabasci & Stevens 2013)

5.4 Recycling of polycarbonate waste

Recycled polycarbonate is made from a pre-consumer or post-consumer waste. The term pre-consumer waste is used for recycled material, which is derived from industrial scrap. Pre-consumer waste is also called post-industrial waste. Post-consumer PC waste is derived from plastic products. (ISO 15270 2008) Recycled PC is used, for example, in the covers of mobile phones (Tillman et al. 1994) (Nokia 2013).

Post-consumer PC waste is collected from CDs and milk and water bottles and automobiles (Scheirs 1998). PC parts are used in car lamps and body panels. The origin of pre-consumer waste is runner scrap, defected parts and contaminated materials which are produced by injection moulding. The term pre-consumer recycling does not cover materials, which are reprocessed directly after moulding. The quality of this material may not be as high as that of material reground by a recycling company. (Järvinen 2008) The reciprocating screw in moulding machine is designed only to melt materials, not mix them (Tuomisaari 2014). Badly mixed materials can result in surface defects such as flow marks.

Mechanical, chemical and thermochemical recycling methods can be applied to PC. Mechanical recycling is currently the most viable method. Other methods are not yet widely used. A flow chart for mechanical recycling of PC is shown in Figure 18. Similar processes are used for pre-consumer and post-consumer waste. Processes are also applicable to PET waste. All processes do not require individual equipment. For example, compaction, grinding, removal of foreign materials and granulating are possible to perform in one machine.

The collection and separation steps are different for post-consumer and pre-consumer waste. Pre-consumer waste comes from moulders and is relatively pure. Screens are however used for purification (Tuomisaari 2014). The quality of post-consumer PC waste can be lower than that of pre-consumer waste. PC water containers are used in offices and public spaces where they are subjected to impurities, although the impurities are mild compared to those of an outdoor environment. PC water containers are collected by a water supplier, so the waste stream is controlled. This yields a higher recovery rate of PC scrap than for example in the case of PET beverage bottles. (Silvennoinen 2014) Contaminated PC bottles are separated by optical separation. Optical separation is viable for transparent parts, but dark coloured products must be separated with different techniques (Froelich et al. 2007).

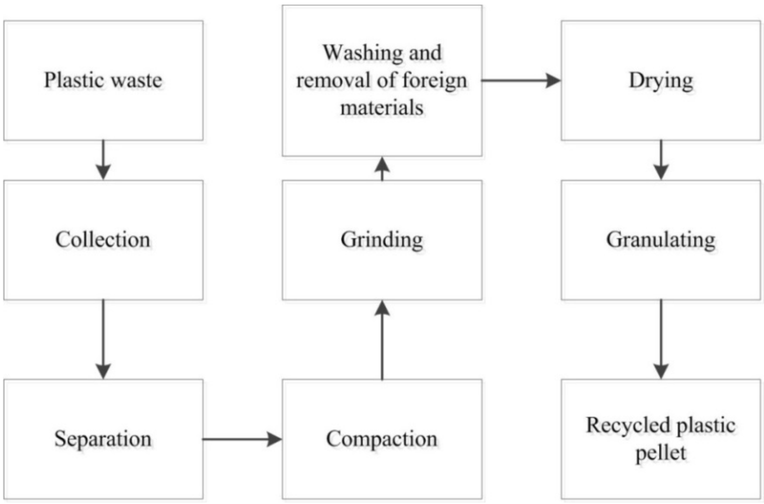

Figure 18. Recycling of plastics contains many steps. Similar processes are used for pre-consumer and post-consumer waste. Collection and separation of pre-consumer waste is more straigthforward than that of post-consumer waste.

Some PC grades can be recycled several times without reduction in physical properties. Rosato et al. (2000) reported that the melt flow rate and impact resistance of natural coloured high viscosity PC remained at the same level after three regrinding cycles. However, the yellowing index was increased. Melt flow rate of the medium viscosity flame retarded PC was increased after three regrinding cycles. Regrinding of high viscosity PC has the highest probability for good material properties.

Pérez et al. (2010) studied how several reprocessing cycles affect the properties of PC. Tensile properties of samples remained constant even after 5 - 7 recycling cycles. The impact strength of the samples was already significantly reduced after 2 cycles. Molecular weight was reduced after 2 - 3 reprocessing cycles caused by the scission of polymer chains.

5.5 Recycling of polyethylene terephthalate waste

Most of the post-consumer PET waste comes from beverage bottles. In 2012, 60 million PET bottles were recycled which accounts for 52 % of all post-consumer PET bottles in Europe (Petcore Europe 2012). The recycling of PET is economically viable since the price of recycled PET is estimated to be similar to that of virgin PET (Strong 2006) (Welle 2011).

The recycling of PET beverage bottles is a well-known and successfully used process. PET is recycled by many recycling methods from mechanical recycling to chemical recycling. PET bottles, which are used in PC/rPET blend, are mechanically recycled. The recycling of post-consumer waste requires many steps such as collection, handling, sorting and cleaning before it can be reused in production. The steps are shown in Figure 18.

The recycling of PET bottles is effective, but the use phase of the bottles is not as well controlled as that of PC water containers. PET bottles are sometimes used to store chemicals which affect material properties or leave residuals on the material, for instance. (Silvennoinen 2014) To fulfil food safety and avoid discolouring virgin PET is needed to blend with recycled PET. According to Shen et al. (2011) a PET bottle can contain a maximum of 35 % recycled material.

Consumers play a large role in the collection of PET bottles. Post-consumer plastic waste is collected from roadsides, drop-off programmes or commercial collection systems. PET plastic waste is derived from beverage bottles and packages. Collection requires transportation and manual work. (Franklin Associates 2011) The collected waste is delivered into material recovery facilities where the material is sorted and separated. Sorting is performed either manually or automatically based on colour separation (Shen et al. 2010). Other possible separation methods include magnets, air classifiers and sink float methods (Franklin Associates 2011) (Scheirs 1998).

PET waste is compacted into bales which are processed in reclaimer facilities. Bales are broken and foreign material is removed from the PET waste. Normally the foreign materials are aluminium and HDPE or PP from the bottle cap. The waste is washed, if necessary, before it is granulated into flakes. (Franklin Associates 2011) Solid-state condensation is performed after granulating. Solid-state condensation increases the molecular weight of the plastic by increasing the length of polymer chains without melting the material. It is a common process in PET recycling. Solid state condensation is not used for PC. (Silvennoinen 2014) (Rüdiger 2014) (Buckel 2014).

Flakes are converted into pellets and chips. Pellets and chips are further extruded into fibres or they are used for plastic products or blended with other plastics. Most of the PET waste is processed into fibres. (Shen 2010) Flame retardants and other additives are mixed with recycled material in compounding (Silvennoinen 2014). Compounding is also used to produce plastics blends, such as PC/rPET.

6 BIO-BASED PLASTICS

6.1 Definition of bio-based plastic

In this thesis, the term bio-based plastic is defined as a plastic containing carbon from animals, plants or micro-organisms. Specific limit for the required bio-based carbon content is not set. Other definitions for bio-based plastic also exist. Sometimes bio-based plastics are just called bio-plastics. However, the prefix bio has other meanings such as biodegrading or biocompatibility which make the understanding more difficult. Biodegradable plastics degrade in anaerobic conditions and this phenomenon is used to dispose plastic products. Biocompatible plastics are used in medical applications and they are compatible with living organisms (Kabasci & Stevens 2013).

The Sustainable Biomaterials Collaborative (SBC 2014) defines a bio-based material as a material in which the carbon comes from contemporary biological sources. SBC uses term bio-plastic for plastics which contain 100 % of bio-based carbon. The ASTM defines bio-based material as an organic material in which the carbon is derived from a renewable resource via biological processes. The amount of bio-based carbon in the material is estimated with ASTM D 6866 (2012) standard. The standard determines the bio-based content by comparing the amount of carbon 14 in the unknown sample with the reference sample. The European Committee for standardisation defines bio-based plastics as plastics which are derived from a biomass. A biomass is a biodegradable organic material originated from plants, animals or micro-organisms. (Kabasci & Stevens 2013) The US Department of Agriculture (USDA 2014) defines bio-based products as commercial or industrial products (other than food or feed) that are composed in whole, or in significant part, of biological products, renewable agricultural materials (including plant, animal, and marine materials), or forestry materials.

Bio-based plastics are not necessarily biodegradable, such as bio-based (PE). Biodegradable plastics may not contain bio-based raw materials, but they are still called bio-plastics. Biodegradability was discussed with other recycling methods in the previous chapter. Figure 19 divides plastics based on the biodegradability and whether the material is a fossil-based or bio-based.

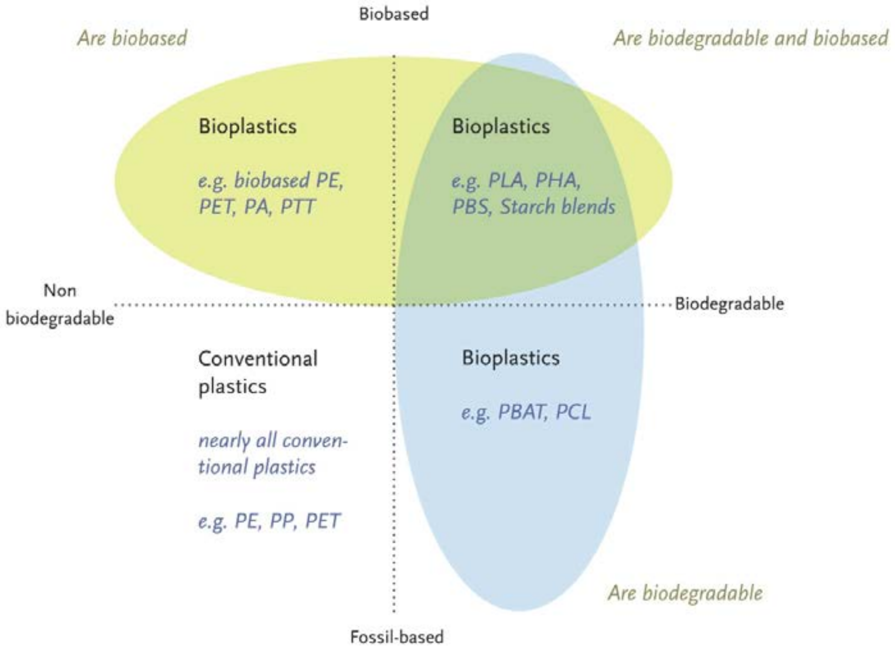

Figure 19. The classification of plastics based on the biodegradability and source of raw materials. (European Bioplastics 2014a)

Bio-based plastics can also be defined as partly bio-based or bio-replacement plastics. Partly bio-based materials contain both bio-based and petroleum-based carbon, whereas fully bio-based plastics like PA 11, PLA or PHA contain only bio-based carbon. PA 410 and PTT studied in this thesis are partly bio-based plastics, since they contain petroleum-based components. PTT is a bio-replacement plastic since its properties are similar to the petroleum-based version (Kurian 2005). Currently, a fully petroleum-based PA 410 is not in the production.

Some companies have their own definitions and terms for the bio-based or biodegradable materials. For example, Nokia (2011) uses term eco-plastic which can mean bio-based or recycled plastic. DuPont (2014b) uses term renewable sourced material for a material which contains minimum of 20 wt-% renewable sourced ingredients.

6.2 Advantages of bio-based plastics

The reasons to use bio-based plastics depend on the product. In packaging, the use of bio-based and biodegradable plastics reduces waste that ends up in a landfill. In packaging, the desired property is specifically the biodegradability. Bio-based plastics are used also for marketing purposes. Bio-based raw materials can give an impression of an environmental friendly product.

Bio-based plastics can reduce the carbon footprint of the product. The reductions in the carbon footprint are not necessarily significant. For example, the study by Hottle et al. (2013) show that carbon footprint of the bio-based PLA granulates and petroleum-based PET granulates were at the same level. The study state that bio-based plastics do not have clear advantage in any environmental indicator when compared with petroleum-based plastics. Similar conclusion was drawn in the study by Vercalsteren et al. (2010).

Replacing some of the petroleum-based material with bio-based monomers can reduce GWP and energy usage. In study by Shen et al. (2011) the non-renewable energy usage and GWP of partly bio-based PET were 21 and 25 % lower, respectively, than those of petroleum-based PET. However, recycled petroleum-based PET had still lower energy usage and GWP than bio-based PET. In that scenario, recycling and use of bio-based raw materials were almost equally effective methods to reduce the environmental impacts.

Bio-based plastics are also used to avoid the dependence on oil. Although, bio-based raw materials do not contain oil, the production processes require oil for transportation, for instance. The study by Franklin Associates (2007) show that the production of bio-based PLA required less fossil fuels than production of PET, although the total production energy (fossil fuels and non-fossil fuels) of PLA was higher than that of PET.

6.3 Disadvantages and difficulties of bio-based plastics

Petroleum-based plastics replaced bio-based plastics in the 1940s due to low costs of crude oil. Cost of crude oil derivatives has stayed relatively low, which has supported the production and use of petroleum-based plastics. Recently, some of the bio-based raw materials have become cheaper than crude oil. New processes, which allow production of bio-based plastics with reasonable costs, increase the use bio-based plastics. (Mittal 2012)

Prices for selected raw materials are shown in Figure 20. The figure shows that prices for crude oil and bio-based materials fluctuate greatly. In 2012 the price of crude oil was higher than that of bio-based raw materials, such as sugar, castor oil and sebacic acid. Sebacic acid is refined from castor oil and used in bio-based plastics (Kabasci & Stevens 2013). Price of the crude oil is dependant of the demand and supply. International crises such as accidents, extreme weather conditions and wars also affect prices. In 2014 supply of the oil was increased and the price lowered. The increased production of polymer from shale gas in the USA is a factor that changes fossil fuel markets. (Niskakangas 2014)

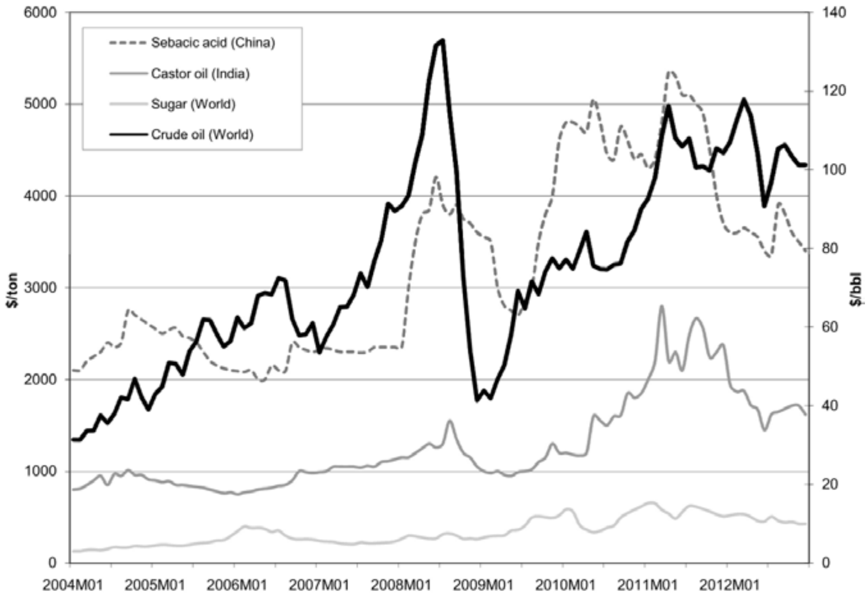

Figure 20. Prices of crude oil and bio-based oil are not constant. Large variations in prices are possible, but generally raw materials have become more expensive. (Kabasci & Stevens 2013)

Raw materials for bio-based plastics compete with food chain and bio-fuels, although the production volume and land usage are still very low. Global agricultural area is 5 billion hectares from which bio-based plastics required 400 000 hectares in 2012. That corresponds less than 0.01 % of the total agricultural area. (European Bioplastics 2014b) The competition with food chain impairs the reputation of bio-based plastics regardless of the actual land usage. The efficiency in the land usage is increased with transgenic plants. Transgenic plants are, however, restricted by the law, for example in Europe (Hausmann & Broer 2012).

According to Tabone et al. (2010) production of bio-based plastics increases some environmental impacts. For example, the production of bio-based PLA and PHA increases eutrophication, carcinogens formation and ozone depletion when compared to PC or PP. However, GWP and fossil fuel depletion of the bio-based plastics were significantly lower than those of PC. The production of bio-based plastics requires fertilizers, pesticides and chemicals for fermentation and other processes which increases the environmental impacts of the production. The environmental benefit of the bio-based plastics is clearly dependable on the studied attribute. Comprehensive evaluation of the environmental impacts of bio-based plastics should be evaluated with various impact categories.

6.4 Bio-based plastics markets

Bio-based plastics do not hold large fraction from plastics markets. It was estimated that only 1 % of all plastics in the market is bio-based (Babu et al. 2013). The fraction is predicted to reach 3 % until 2020. The annual production capacity in 2020 is estimated to be 11 - 12 million tonnes. In 2011 the production capacity was 3 - 4 million tonnes. Bio-based plastics markets are growing mostly due to use of bio-based PET and PP. (Carus et al. 2013)

Limited availability and higher price delay the implementation of bio-based plastics. Higher price in comparison to petroleum-based plastics does not necessary rule out the use of bio-based plastics. In fact, in the study by Carus et al. (2014) it was observed that customers and other market actors are willing to pay more for bio-based materials in some applications. The use of bio-based materials increases the costs for 10-30 % in most cases. In some special applications, such as wall plug made from bio-based PA, additional costs can be even 300 %. In addition, the price of intermediate products was increased more than the price of the end customer products. The willingness to pay higher price depends much on the product. For example, environmentally friendly cars should pay cost the same as "normal" cars (Khare 1999), but an environmentally friendly toy or food packaging can cost 10 - 25 % more than conventional products (Carus et al. 2014).

6.5 Raw materials of bio-based plastics

Bio-based plastics can be completely bio-based or a blend of petroleum-based and bio-based polymers. Bio-based raw materials are derived from corn, sugar cane, castor oil plant, soy or from cellulose. (Alvarez-Chavez et al. 2012) PTT and PA 410 which are studied in this thesis, contain bio-based raw materials from corn starch and castor oil, respectively.

Bio-based raw materials are classified as naturally occurring polymers and synthesised polymers. Naturally occurring polymers such as starches, lignin, cellulose and rubber are produced in plants. Elastin, fibrous proteins and collagen are examples of synthesised polymers, which are derived from bacteria or algae. (Hausmann & Boer 2012) Agricultural materials cannot be used for materials without converting them into polymers or other intermediate products. Crops are processed by fermentation, chemical reaction or modification to produce suitable polymer chains for plastics. Chemical modification is made by acetylation, succinylation, phosphorylation, limited hydrolysis and specific bond hydrolysis. The purpose of chemical modification is to treat the material with a specific chemical which causes desired reactions. Physical modification requires heat and pressure to break chemical interactions. (Wool & Sun 2005) Even though raw materials for the polymers and intermediate products do not possess toxic substances, processes may require the use of hazardous chemicals. (Alvarez-Chavez et al. 2012)

Bio-based feedstock for engineering plastics is mainly used to produce bio-based versions of existing monomers. The bio-based monomers have similar properties as their petroleum-based counterparts and are easily taken in production. Their waste handling and recycling do not differ from those of the petroleum-based plastics. It was expected by Babu et al. (2013) that in the future, bio-based plastics vary more from the petroleum-based plastics.

6.5.1 Corn starch

Corn is used as a resource for starch, because it contains more starch than other cereals, and its separation from germ and pericarp is easy (Wool & Sun 2005). The USA is the largest producers of corn. Corn is used for livestock feed, food and industrial applications including ethanol. In the USA, 39.4 % of the corn in 2010 was used for livestock feed and 34.9 % of the corn crop was converted to ethanol. 15.2 % of the corn was exported and 10.5 % was used for food and other industrial applications. (Kabasci & Stevens 2013)

Starch-based plastics are used in food containers, packaging and bone fillers in orthopaedic implants (Babu et al. 2013). Starch is used as an intermediate for the glucose production from which the glucose is processed into plastics. Starch extraction is known as the wet milling, because it requires large amount of water. The wet milling of the corn includes following steps: preparation, steeping, germ removing, grinding, fibre and gluten removing and starch washing. Corn oil and protein is recovered from the extraction process. (Wool & Sun 2005) The preparation includes cleaning the corn kernels. The steeping is placed inside steeping tanks containing 0.1 - 0.2 % sulphuric acid solution for 36 - 48 h. Water diffusion, lactic acid bacteria and yeast growth take place during the steeping. The processing temperature is in the range of 36 - 51 °C (Ramirez et al. 2008). Low temperatures prevent yeast growth and excess heat denatures the protein. (Wool & Sun 2005) After the steeping, starch is separated from germs, proteins and fibres. Corn kernels are mechanically opened and the separation is performed in several hydrocyclones. The separation in hydrocyclones is based on different densities of the materials. The germ separation is the first separation step followed by fibre and gluten separation. Gluten is formed from protein matrix and fibres. Impurities in the process such as sand are screened with filters. (Wool & Sun 2005) The resulting starch is used directly to produce plastics or it can be processed into ethanol. Ethanol is used as fuel or processed into glucose and glycerol. The fermentation of glucose and glycerol with a suitable organism results in 1,3-propanediol (PDO), which is a raw material for PTT.

6.5.2 Castor bean

Castor bean plants grow wild in tropical Africa and Asia. Main producers are India, China and Brazil. The castor oilseed production was 1 million tonnes in 2010. The production of castor oil has doubled in 10 years. The total production volume in 2000 was 517 thousand tonnes. Castor oil can be processed into sebacic and undecenoic acids, which can be further processed into plastics. The processing of castor beans into these monomers is shown in Figure 21. The castor bean plant grows best at low humidity, in clay soil and at temperatures between 20 and 26 °C. Castor seeds are not suitable for human or animal food due to toxicity (Mittal 2012). Castor seeds contain ricin, ricinine and allergens (Ogunniyi 2004). Because of the toxicity, castor plants are not grown for ornamental, food or feed purposes. However, it was reported by Ogunniyi (2004) that castor cake can be detoxified by caustic soda, ammonia, lime and heat. Detoxified cake can be used as feed.

The oil content in castor bean is high, typically 40 - 60 % (Kabasci & Stevens 2013). Oil is extracted from beans by mechanical pressing and solution process. Heptane, hexane and petroleum ethers are used for extraction. Castor oil does not contain toxic components and it is used in many industrial applications such as in soaps, lubricants, paints and motor oil. (Ogunniyi 2004) Castor oil is also used in medicinal products such as laxatives and counter constipation (Mutlu & Meier 2010). Extracted oil is usually refined to remove contaminants (Mutlu & Meier 2010) (Ogunniyi 2004). The chemical composition of the oil is studied to remain constant regardless of the country of origin (Mutlu & Meier 2010).

Castor oil is solved to ricinoleic acid which is converted to sebacic acid by alkali fission or to undecenoic acid by pyrolysis. The alkali fission is performed by treating the ricinoleic acid at 180 - 270 °C with NaOH or KOH. The reaction products are sebacic acid and 2-octanol. Sebacic acid can be used to produce polyamides such as PA 1010, PA 610 and PA 410. The side product 2-octanol is combusted (Kabasci & Stevens 2013) or used as plasticizer in the form of dicapryl esters (Ogunniyj 2004).

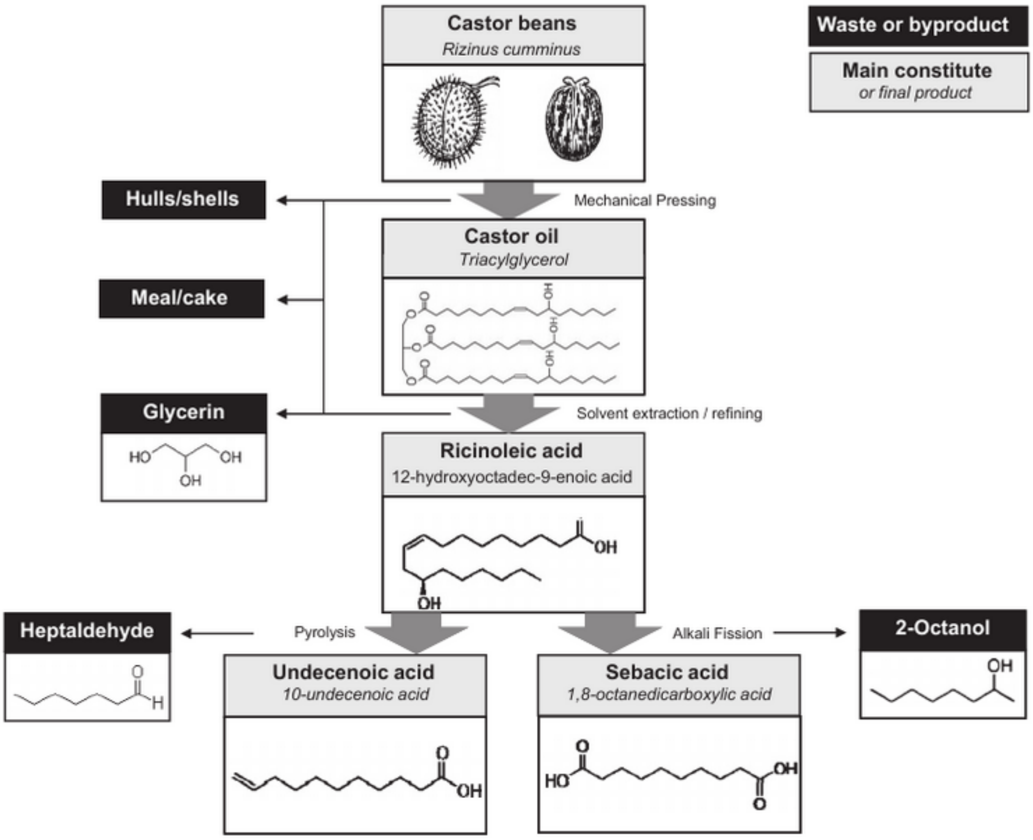

Figure 21. The production of sebacic acid from castor beans. (Kabasci & Stevens 2013)

7 DEGRADATION OF PLASTICS

The plastics in base stations are subjected to demanding environments in their service life. Same devices are installed outside or inside. Commonly same materials are used for the indoor and outdoor products to simplify the purchases and production. The plastics in this thesis are intended to be used in covers or structural parts of the base stations. Common example product is a solar shield which is used to cover a base station from the UV-radiation and excess heat. Therefore materials must sustain outside temperatures from -35 - +55 °C. However, surface of solar shields can absorb infrared heat and the surface temperature can exceed 55 °C.

Plastic parts are also exposed to thermal cycling during transportation. Since the base stations contain metals and plastics, it is important that the different coefficients of thermal expansion (CTE) do not cause fracture of the parts. In addition, the CTE mismatch, creeping and relaxation of internal stresses cause loosening of the screws, which may result in dropping of the parts, for instance.

The plastics are exposed to many chemicals during the production, installation, use and maintenance. Common substances such as perfumes, water displacements and wasp sprays are detrimental for plastic parts. An urban and industrial environment can contain chemicals such as sulphuric acid. In outdoor environment, plastics are also subjected to dust, fungi, moss and pests. In addition, humidity and water cause changes in materials. Plastic parts are not allowed to fracture or dissolve during their use phase due to contact with chemicals. Plastic covers are visible parts, so notable changes in the appearance are not allowed.

The resistance of plastics to outdoor environments are discussed in the following chapters. Degradation mechanisms of PC, PC/PET, PTT and PA in different conditions are briefly introduced. Degradation mechanisms for virgin PC and PET are discussed, because mechanical recycling of plastics does not alter chemical composition. Degradation mechanisms of bio-based PTT and PA are comparable to petroleum-based counterparts, since their polymer chains are similar. In addition to literature, the suitability of the materials for outdoor use is evaluated by a series of material tests.

7.1 Degradation in water

Water causes chemical and physical reactions in plastics. Water is absorbed by the plastic as free or bound water. (Harvey 2005) PET, PTT, PAs and PC are all affected by water. In these plastics, the glass transition temperature (T_g) and molecular weight are reduced, when the material absorbs water. (Brydson 1999) The reduction in the T_g weakens the mechanical performance of the material due to depolymerisation.

Polyesters (PC, PET and PTT) contain an ester group, which is susceptible to hydrolysis. Hydrolysis of an ester link causes chain scission. (Brydson 1999) After all, water absorption of polyesters is relatively low, only 0.2 - 0.4 %. The susceptibility of PC to the water absorption is due to oxygen found in the carbonate group (CO_3) in the chemical structure of PC (Megat-Yusoff et al. 2013). Water causes the carbon linkage to split into alcohol and carbon dioxide. The degradation is accelerated due to residues of acidic and basic catalysts. These catalysts are in the contact with polymers in polymerization processes. (Harvey 2005a)

The degradation of PC by hydrolysis is most severe at high temperatures. Humid resin causes visual defects to the moulded part. According to Rosato et al. (2000), hydrolysis is recognized from the silver streaks on the surface of the part. Moisture content over 0.02 % results in waviness in the product and reduction of mould filling (Goodship 2004). The water absorption of PC at room temperature is low especially when comparing to that of PAs. PAs absorb more water than other engineering thermoplastics; some PA grades absorb moisture more than 10 %, for instance. Tensile strength and modulus may be reduced by 20 % with water absorption. As with other plastics, water absorption increases with temperature, therefore moisture is most damaging during processing. (Strong 2006) Humid granules during the moulding cause waviness in the PA products and a loss of mechanical properties (Goodship 2004). The high water absorption rate reduces dielectric strength of the material which weakens insulation. The water absorption rate depends on the PA grade. PAs with short polymer chain (PA 6, PA 46 and PA 66) absorb more water than PAs with long polymer chain (PA 11 or PA 12). (Järvinen 2008)

7.2 Thermal stability

High temperatures degrade polymer chains and cause a loss of mechanical properties. Plastics materials in base stations shall have operating temperature of 85 °C. This requirement rules out some of the plastics, which are otherwise useful. For example, the maximum operating temperature of ABS is 67 °C (Mills 2005). High operating temperatures limit also the use of PET. PET has glass transition temperature around 80 °C, so there is a risk of failure, if a PET part is used near this temperature.

PC and PA 6.6 can tolerate higher temperatures than ABS and PET. According to Mills (2005) the maximum operational temperature of PC and PA 66 in dry air are 96 °C and 120 °C, respectively. Deflection temperatures of PA 410 and glass filled PTT are 110 (DSM 2014) and 200 °C (DuPont 2014c), respectively. High deflection temperature suggests that these materials are useful at 85 °C.

PC has high thermal stability because it has only two types of hydrogen: methyl and aromatic. The thermal degradation of the PC occurs at temperatures above 300 °C, which are possible during injection moulding (Montaudo et al. 2002). According the to study by Jang and Wilkie (2004), the main degradation methods of PC are the chain scission of isopropylidene linkages and the hydrolysis or alcoholysis of carbonate linkages. At the beginning of the degradation, rearrangement of some carbonate linkage occurs and CO_2 and H_2O begin to evolve. Different degradation paths occur in the material at the same time. Some chains degrade by hydrolysis and alcoholysis and some by chain scission.

Thermal stability of PAs is affected by the distance of the amine groups in the polymer chain. The creep resistance and deflection temperature are increased, when the distance between amine groups is decreased. High amine group concentration also improves the chemical resistance and mechanical strength. (Brydson 1999) The amine group concentration and thermal stability of PA 410 are lower than those of PA 46 and PA 6. On the other hand, the water absorption of PA 410 is lower than that of PA 46 and PA 6. (DSM 2014) (Brydson 2011)

7.3 Outdoor degradation

UV radiation from the sun causes material changes in plastics in outdoor environment. Chemical structures absorb radiant light energy, which degrades the chemical bonds (Brydson 1999). Air can also contain impurities, which increase the degradation of plastics (Strong 2006). Outdoor environment and solar radiation cause brittleness, colour changes and formation of surface cracks (Fechine et al. 2002). UV radiation heats different parts of the product differently and causes buckling and warpage. Heated areas are in compression and shaded areas are in tension. Generally the studied materials are stable to light and perform better in sunlight than commodity plastics like PVC or PE. (Summer & Rabinovitch 1999)

Degradation mechanism of PC in outdoor weather has been studied in many studies. Most of the studies are conducted by accelerated weathering tests. (Diepens et al. 2011) Real behaviour of the material should be studied in real environment with real operating time (Harvey 2005b). Testing of plastic covers can be arranged in real environments, but the required exposure time for the parts of base stations is too long. The service life of the plastic parts of base stations is expected to be 10 years. If outdoor resistance or UV durability is tested in laboratory, the conditions should correspond to real operating environment. For example, wavelength of the radiation of UV lamp should be in the range of the solar radiation, 295 - 380 nm. Wavelengths shorter than 295 nm cause degradation which does not occur in real environments. (Wypych 1999) In UV radiation, PC is degraded by two methods: photo-Fries rearrangement and photo-oxidation. The photo-Fries rearrangement occurs, when the wavelength of the light is shorter than 300 nm and photo-oxidation occurs, when the wavelength is longer than 300 nm. The most dominant degradation method of PC in the solar radiation is the photo-oxidation, even though small amount of photo-Fries reactions can occur. The photo-oxidation is initiated by radicals. (Diepens & Gijsman 2007)

The UV degradation of PC results in yellowness on the surface and loss of impact strength. An outdoor test of PC with and without UV stabilizers showed that without UV stabilizers the impact strength of the PC is significantly reduced (Massey 2007). In UV radiation, mechanical properties of recycled PC are degraded faster than those of virgin PC. Pérez et al. (2010) found out that tensile strength of virgin PC only increased from 61.7 MPa to 62.3 MPa after 600 h in an accelerated aging test. The 600 h accelerated test corresponded to 22 years of outdoor use. If PC was reprocessed more than once, the tensile strength of the material was degraded significantly after 8 years of outdoor use. Tests were, however, conducted without UV stabilizers.

As PC, PAs also suffer from outdoor degradation but their UV resistance can be improved with carbon black. Carbon black prevents absorbance of the solar radiation into the material (Brazel & Rosen 2012). Some embrittlement of unfilled PA is observed after an outdoor exposure. In PAs, wavelengths over 340 nm cause degradation by hydroperoxidation and wavelengths lower than 300 nm cause degradation by photoscission. (Massey 2007)

PTT and PET are resistant to UV radiation, especially if they are stabilized with carbon black. Without colouring additives PET and PTT suffer from yellowness in UV radiation (Lauttia 2014) (Silvennoinen 2014). According to Kurian (2005) PTT resists UV radiation better than other fibres such as PA 66 or PET. Even though the UV resistance of PET is lower than that of PTT, mechanical properties of PET are maintained in outdoor applications. For example, over 90 % of the tensile strength of a PET sample was retained after 3 years of outdoor exposure (Massey 2007).

7.4 Degradation due to chemicals

Solvents and other chemicals cause degradation and dissolution of plastics. The dissolved polymer chains can form new chains, which change appearance and mechanical properties of plastics. (Brazel & Rosen 2012) Chemicals cause also environmental stress cracking (ESC). ESC is a failure mechanism which occurs when a product is subjected in stresses and strains in a specific fluid. Stresses and strains can be derived from external loads or they are formed during moulding. The fluid may end up on the surface of the product from aerosol sprays, paints, labels, adhesives and leaks from other systems. It is estimated that 15 % of the failures of plastic parts is due to ESC. The failures of motor cycle helmets made of PC are a familiar example of ESC. Chemicals in adhesive labels and paints caused micro-cracking and degradation of PC which weakened mechanical properties. ESC also degraded babies' feeding bottles made of PC. The bottles were cracked when they were exposed to insect spray. (Wright 1996)

Fluids affect plastics by two methods: by attacking chemically or absorbing into the critical zones of the part. Chemically attacking fluids cause chain scission, chemical modification and cross-linking by hydrolysis, oxidation or chlorination. Other chemicals are absorbed into micro-yielded or stress-dilated zones and they cause weakening of mechanical strength. (Wright 1996) Amorphous plastics like PC dissolve easier than crystallized plastics such as PA, PET or PTT. Crystalline bonding forces improve chemical resistance. Crystallized plastics are dissolved easier when temperature is increased. (Brazel & Rosen 2012) Chemical resistance of the studied plastics is evaluated with a chemical exposure. The hypothesis is, if PC can tolerate the contact with the chemicals, PC/rPET blend, PTT and PA 410 can also tolerate the chemicals.

8 SCOPE OF THE STUDY

8.1 Research problem

This study aims to answer, how large environmental impacts are related to recycled and bio-based plastics. The environmental impacts are assessed with primary energy demand and greenhouse gas emissions. The environmental attributes are compared with those of virgin petroleum-based PC. Another subject is the technical performance of the materials. Even though recycled and bio-based plastics should have similar chemical structure as those of virgin petroleum-based plastics, differences during processing can have an effect on the behaviour of materials.

8.2 Purpose of the study

The purpose of the study is to evaluate, whether the environmental impacts of the product can be reduced by using recycled or bio-based plastics and whether the LCA tool can make a difference between these materials. Different methods to treat recycling and bio-based materials in LCA are studied to understand, what should be taken into account when evaluating the environmental burden of these materials.

The results of LCA and material tests provide information for the designers about the new materials. The selected material tests represent the basic requirements for plastic materials in base stations. The studied materials are not planned to replace materials in the current products, but the results can be utilized when designing future products, which may have different requirements than current products. The purpose of the material testing and analysing is not to evaluate the polymer structure or improve it.

Weathering resistance of plastics is evaluated with an accelerated aging test and outdoor exposure. The accelerated aging test is performed at 85 °C and 85 % relative humidity. At these conditions hydrolysis degrades materials much faster than at room temperature. Exposure time is 2 000 h and it is assumed to be enough to reveal differences between materials. In addition to humidity and heat, UV radiation is detrimental for most plastics (Wypych 1999). Material is degraded by one these factors and by combination of them (Massey 2007). Outdoor exposure provides information, how materials perform in the environment which contains real life impurities, temperatures, heat and sun shine.

Testing is made up with water absorption, temperature cycling and chemical exposure. Each of these tests is concentrated only to one material property. Water absorption is property, which depends on polymer structure and the absorptivity is easily measured by scale. Water absorption is not a critical parameter of the covers, but the testing is used to study basic properties of plastics. Temperature cycling is used to evaluate, how materials perform in the real applications during a constant change of temperature. Temperature cycling can cause relaxation of the internal stresses. In the testing, plastic covers are attached into aluminium casings. Aluminium and plastics have different CTE, which causes externals stresses. Variable stress and dimensions may result in loosening of the screws. In chemical exposure plastics are subjected to substances, which are commonly used for lubricating, cleaning or solving. Plastics are also exposed on the insect spray, which is known to be detrimental for plastics (Wright 1996). Visual changes, such as cracking or colour changes are studied in the chemical exposure.

The moulding of the plastics was not studied in details. Observations from the moulding are, however, discussed, because the moulding properties of the materials affected the performance of the materials in testing. Performance of the material in moulding was used to evaluate whether the PC mould can be used for recycled PC or bio-based plastics. A sample product provided possibility to see, how materials behave in complex shaped mould. The information is useful when designing future products.

8.3 Outlines

This study only focuses on the material properties. The scope of the LCA is plastic resin manufacturing prior injection moulding. The moulding and use of the cover is not assumed to make large differences between the materials. Some materials are moulded with lower temperature and pressure, but it is difficult to estimate whether it has significant effect on total energy consumption or emissions of the moulding. The production of additives of the plastics is not considered, because its impact is assumed to be same for each polymer.

Material tests are performed according to international standards and material testing guidelines. The test programme does not contain all the tests which are required for new material approvals of base stations. Tests are used to highlight possible differences between materials. Improvements in material properties are not in the scope of this study. The performance of the materials is compared to that of the current production material. The analysing of the results of the material tests is mainly limited to visual inspection. The appearance of the cover plays an important role, because the cover is a visible part. Some mechanical stresses are, however, applied into the cover during the use, but the function of the cover is not to support other parts or transfer torque and forces. Mechanical loads come mainly from winds, earthquakes, temperature cycling and impacts during assembling, transporting and installing a base station. Suitability of plastics to the outdoor use was evaluated with an outdoor exposure. The plastics were coloured differently, which may affect the results. Outdoor exposures generally require longer testing times than it was possible to include in this study. For this thesis, results were reported after 6 months exposure, which may be short time to reveal major differences. However, the testing is continued after 6 months.

Although new materials for base stations are studied, this study focuses on currently commercially available materials and technologies. Material requirements of base stations were considered already at the selection of materials and tests.

9 STUDIED MATERIALS

This study contained PC, PC/PET blend, PTT + GF, PA 410. Their repeating units of polymer chains are shown in Figure 22. Carbon, hydrogen, oxygen and nitrogen are expressed as, C, H, O and N, respectively. The lines represent covalent bonds between atoms and the hexagons with a circle inside represent benzene rings. The methylene group is shown as CH_2. The figure shows, how the structures of PET and PTT are clearly similar. The only difference between these materials is the number of methylene groups: PET contains 2 and PTT 3 methylene groups. There is a clear difference between PA 410 and the other materials. For example, the repeating units of PC, PTT and PET contain at least one benzene ring and ester group (O=C-O). The polymer chain of PAs also contains nitrogen.

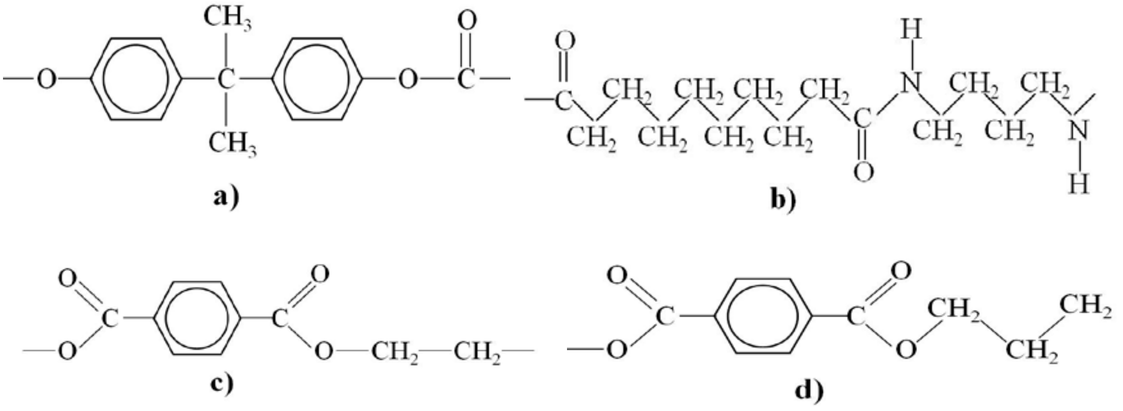

Figure 22. Repeating units of a) PC, b) PA 410, c) PET and d) PTT.

9.1 Polycarbonate

Polycarbonate is an engineering thermoplastic. It is a polyester in which the acidic component is carbonic acid. The impact and heat resistance and also the strength and transparency make it a suitable material for many applications. PC is transparent due to an amorphous structure: the degree of crystallinity is 10 - 40 % (Seppälä 2005). The flame and UV resistance of PC is achieved with stabilizers. PC is also non-toxic and it can be used with food containers. However, PC is banned in some products due to possible residual bis-phenol A (Tolinski 2012). In many applications, PC is blended with ABS, PET or PBT to improve processibility and some material properties or reduce costs. For example, blending with PET improves chemical and moisture resistance, but it may weaken UV durability. (Järvinen 2008)

Properties of PC depend on the viscosity. High viscosity PC is used in water or milk bottles, since the material is suitable for blow moulding. The high viscosity PC is tough enough to be formed into bottle. Low viscosity PC is used for CDs and DVDs. Low viscosity PC is easier to process than the high viscosity PC, but the high viscosity PC is tougher. PC in electrical devices has medium viscosity, which provides good moulding and mechanical properties. The properties of medium viscosity PC are between high and low viscosity PC. (Silvennoinen 2014)

Improved mechanical properties can be achieved with glass and carbon fibre reinforcing. Glass fibre (GF) reinforcing improves the flexural and fatigue strength and dimensional stability. The coefficient of thermal expansion and moulding shrinkage are decreased. Carbon fibre reinforcing improves impact strength, high temperature and wear resistance. (Brydson 1999)

PC is produced from various polyfunctional hydroxyl groups. Most of the polycarbonates are produced from bis-phenol A (2,2-bis-(4-hydroxyphenyl) propane) (BPA) and phosgene. The BPA is produced from phenol and acetone by condensation under acidic conditions. The phosgene is produced from carbon monoxide and chlorine. The processing of polymers by phosgenation process contains hazardous chemicals such as phosgene and dichloromethane. The process also requires water more than 20 times of the weight of PC to be produced (PlasticsEurope 2011). The resulting plastic has, however, good properties like high molecular weight and the processing equipment is fairly simple. (Brydson 1999) The process flow chart of the PC production is showed in Figure 23. PC is also produced by an ester exchange from diphenyl carbonate. The ester exchange reaction requires high processing temperature and a vacuum system which increase the processing costs. (Brydson 1999) PC is mainly produced from BPA and the main producers are Bayer, Sabic, Mitsubishi Engineering - Plastics Corporation (MEP) and Dow.

The production processes of PC are still under development. For example, Fukuoka et al. (2010) introduced the Asahi Kasei production process which uses CO_2 and ethylene oxide as starting materials instead of CO and phosgene. The reaction products of the process are PC and ethylene glycol. The Asahi Kasei process does not require the use of phosgene. It was studied that the Asahi Kasei process reduces CO_2 -emissions by 0.173 t per 1 t of PC resin. The reduction is approximately 4 % compared to the conventional PC production (PlasticsEurope 2014). The Asahi Kasei process contains multiple complex steps and it has the same difficulties as the production of PC from diphenyl carbonate. The Asahi Kasei process is used in four commercial plants. (Fukuoka et al. 2010)

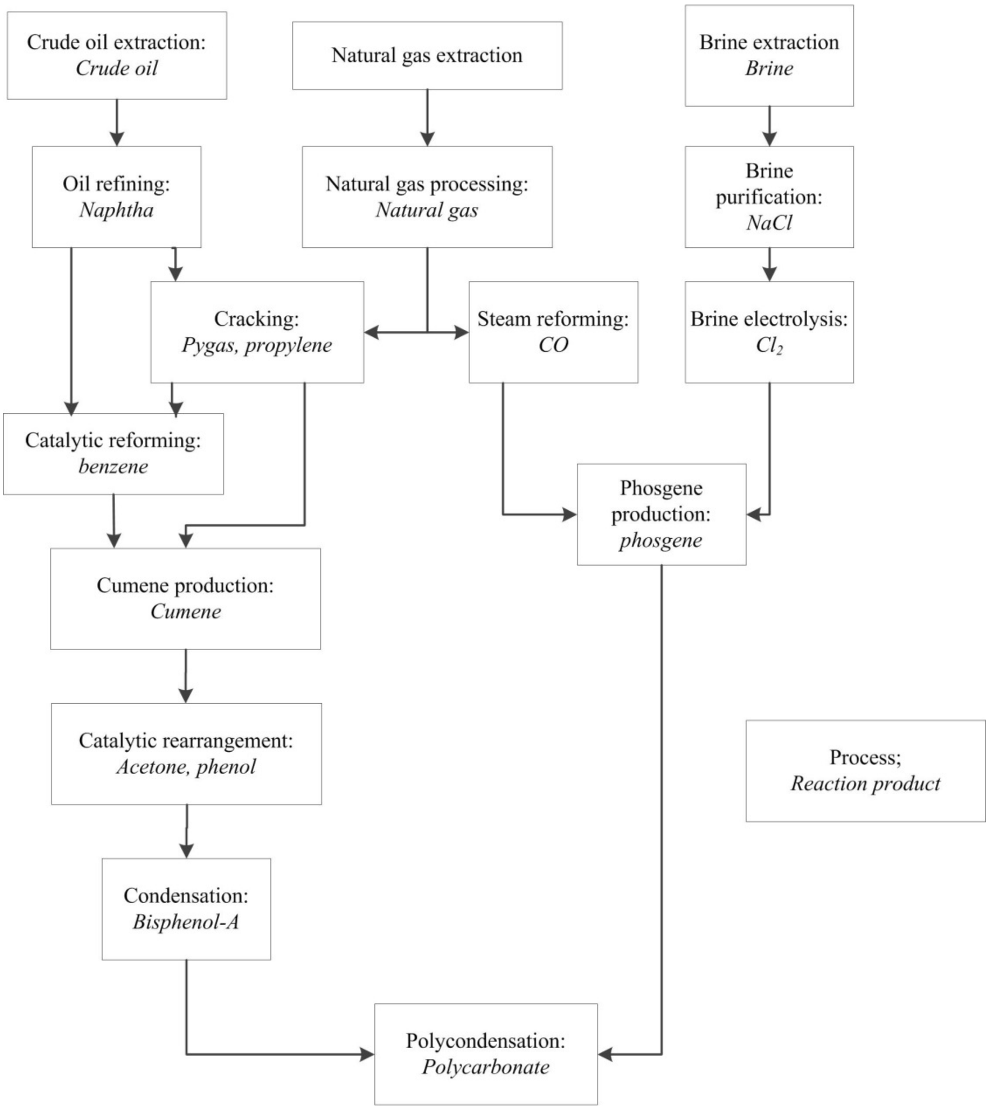

Figure 23. The process flow chart for the PC production. (PlasticsEurope 2014)

9.2 Polycarbonate/polyethylene terephthalate

The properties of plastics can be improved by blending two or several polymers. The chemical resistance of the PC is improved with PET. PET is a reaction product of terephthalatic acid (TPA) and ethylene glycol. TPA is also used to produce other polyesters such as PTT and PBT. (Kurian 2005) PET is a crystalline polymer and crystalline polymers have generally better chemical resistance than amorphous polymers. PC/PET blend also provides better fatigue and low temperature impact resistance than PC (McKeen 2008). PET has good mechanical properties, but it cannot be used in as high temperatures as PC. The glass transition temperature of the PET is near 80 °C, which may be too low for base stations. PET is used in amorphous and crystallized form. An amorphous PET is used in beverage bottles and crystallized PET is used for electrical applications such as transformer bobbins. (Brydson 1999) The crystallization rate of PET is slow which results in slower cycle time in injection moulding in comparison to that of PBT or PTT. (Zhang 2004)

In this study, the PET fraction for the PC/PET blend is derived from used beverage bottles. The flow chart for the PC/rPET production is shown in Figure 24. A PC/PET blend was studied by Fraïsse et al. (2005). They observed that PC waste can be successfully blended with PET waste. The material studied in this thesis contains virgin PC. Possibility to use recycled PC with recycled PET can further improve environmental impacts.

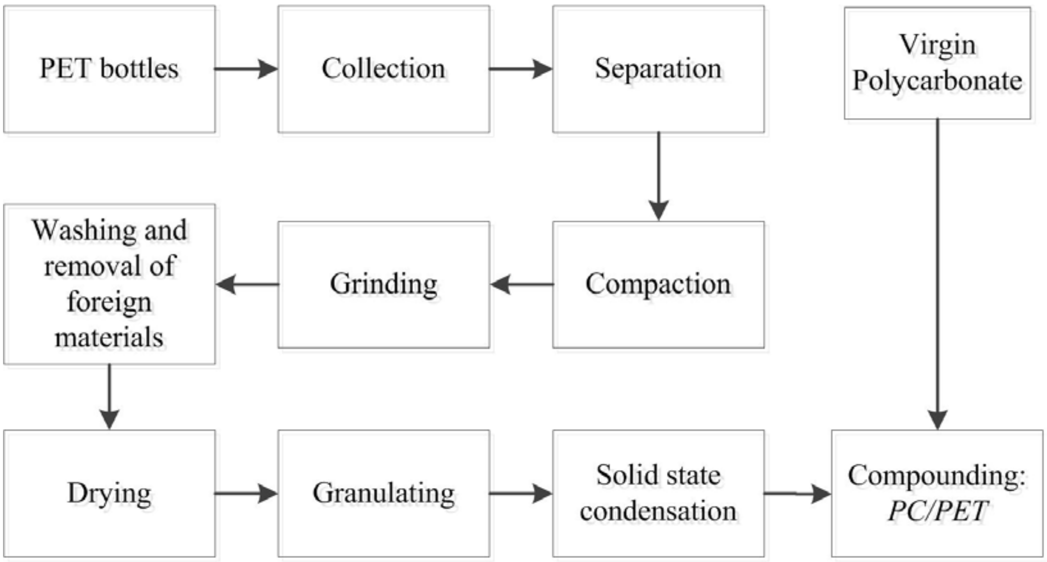

Figure 24. The production of the PC/rPET blend from used PET beverage bottles and virgin polycarbonate. (Shen et al. 2011) (Silvennoinen 2014)

9.3 Polytrimethylene terephthalate

Polytrimethylene terephthalate (PTT) or polypropylene terephthalate (PPT) is a thermoplastic polyester which has similar structure as other common polyesters (PET and PBT). Because of the similar structure, PTT has potential to be recycled in the PET waste stream (Alvarez-Chavez et al. 2012).

Even though the polymer structure is similar, the repeating unit of PTT is shorter than that of PET and the crystal is spring-like. PTT, like other polyesters, is a crystalline plastic. The crystallization rate of PTT is faster than that of PET but slower than that of PBT. PTT is more suitable for injection moulding than PET due to the shorter cycle times (Zhang 2004). However, polymer processing requirements of PTT are more demanding than those of PET (Kurian 2005).

The crystal structure of PTT provides good wear properties which approach to those of PAs. Since PTT is polyester, its water absorption is significantly lower than that of PAs. (Brydson 1999) Mechanical properties of the PTT can be improved with GF reinforcing. For example, the deflection temperature with test pressure of 1.8 MPa for unfilled PTT is only 59 °C (Brydson 1999) whereas deflection temperature of 15 % glass filled PTT is 200 °C (DuPont 2014c).

PTT is mostly used as fibres and it has only recently become material for structural parts such as mobile phone housings and automotive parts. PTT was not studied widely until an economically cost-effective synthesis process of 1,3-propanediol (PDO) was developed in turn of the millennium (Zhang 2004). The PDO is a starting material for PTT. In addition to PDO, TPA or dimethyl terephthalate is required for PTT. (Brydson 1999) In nature, PDO is produced by two-step fermentation from glucose. First, glucose is converted into glycerol by yeast and from glycerol to PDO by bacteria. The fermentation of PDO was discovered already at 1881, but the process did not receive much attention (Biebl et al. 1999). At the beginning of 2000s, Tate & Lyle and DuPont created a process that produces PDO from glucose by single step fermentation (Kurian 2005). A genetically modified strain of E. coli K12 is used in the fermentation (Urban & Bakshi 2009) (Wilke & Vorlop 2008). Use of glucose as raw material reduced material costs (Biebl et al. 1999) and made possible to produce partly bio-based PTT cost-effectively (Harmsen et al. 2014).

DuPont uses corn for raw material of glucose (DuPont 2014d). The production volume of the 1,3-propanediol was 125 kton/year in 2014 of which 90 kton is bio-based (Harmsen et al. 2014). The properties of bio-based PTT are equal to those of petroleum-based PTT. In addition, the bio-based PDO is studied to contain fewer impurities than the petroleum-based PDO. (Kurian 2005) The process flow chart for glass fibre reinforced bio-based PTT is shown in Figure 25. Data for the corn wet milling is derived from (Wool & Sun 2005). Terephthalatic acid processes are according to PlasticsEurope (2014). Details of the GF production are from (PriceWaterhouseCoopers 2012). The polymerization steps of PTT from TPA and corn starch are from (Brydson 1999) and (DuPont 2014d).

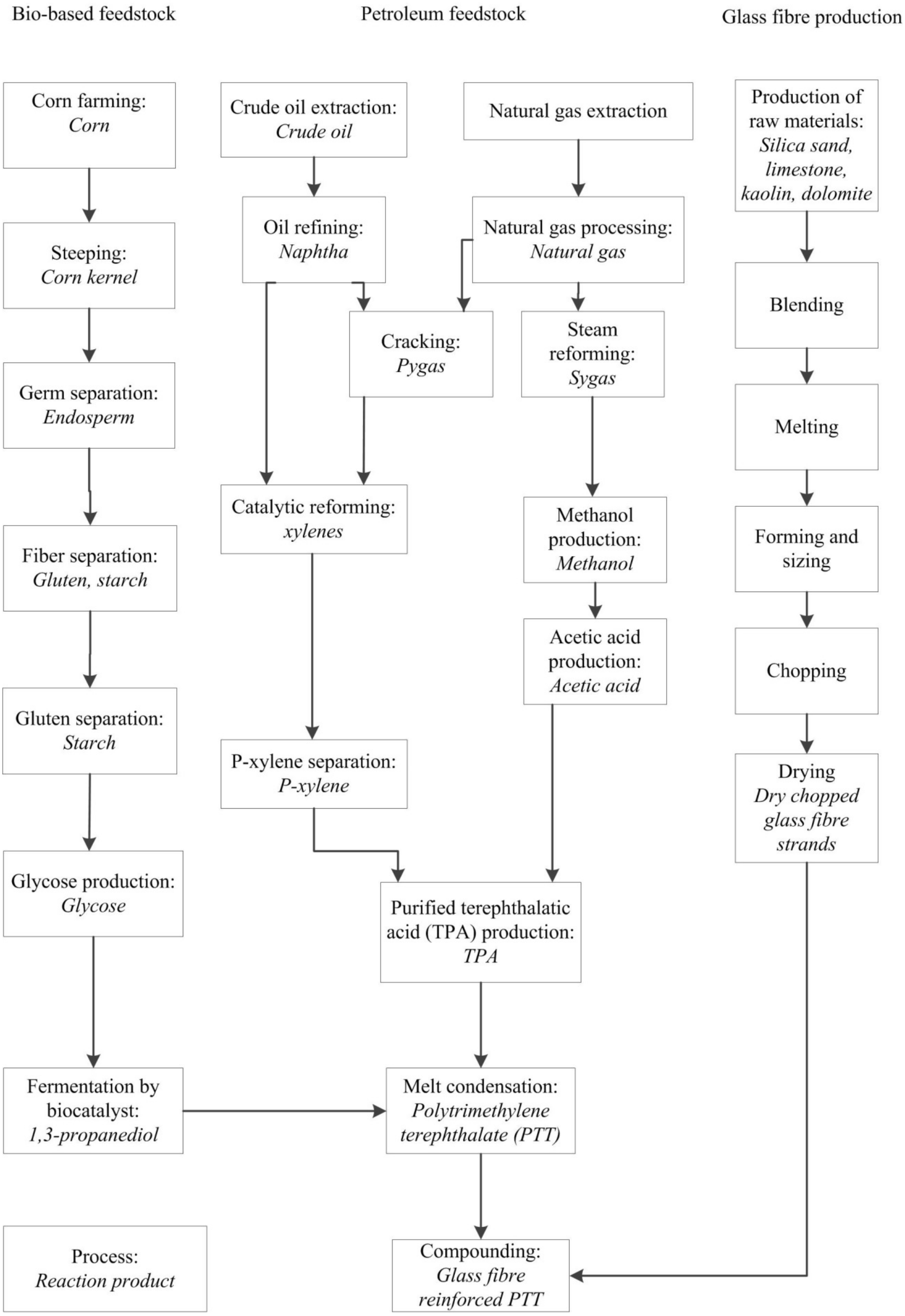

Figure 25. The process flow chart of the glass fibre reinforced PTT production from partly bio-based raw materials. Data is compiled from (Wool & Sun 2005), (PlasticsEurope 2014), (Brydson 1999), (DuPont 2014d) and (PriceWaterhouseCoopers 2014).

9.4 Polyamide 410

PA 410 is a thermoplastic, which belongs to group of polyamides. PAs are colourless or yellowish materials, which are generally called nylons. Nylon is a trademark of DuPont (Brydson 1999). PAs are easily crystallized and they have high melting temperature. They also maintain their ductility and strength even at high temperatures mainly due to hydrogen bonds between polymer chains (Seppälä 2005).

PAs are produced from one or two starting compounds. PAs, which are produced from dicarboxylic acid and a compound which contains 2 amine groups, are named with two numbers, PA 66 or PA 610. Sometimes numbers are separated with comma: PA 6,6, for instance. PAs which are produced from one starting compound are named with one number like PA 6 and PA 11.

PAs are mostly used as fibres for clothing. PAs are also used in electronics since dielectric properties of PA are good at room temperatures and low frequencies. Due to polar chemical structure dielectric properties at high frequencies are reduced. PAs are used also in bearings due to their low coefficient of friction. PAs absorb moisture, which deteriorates dielectric properties and reduces tensile strength and modulus. (Brydson 1999) However, 1 - 2 % moisture content has a favourable effect on PAs, since it increases ductility (Seppälä 2005). The moisture uptake of PA 410 is 2 - 3.5 %, which is significantly lower than that of PA 66. PA 66 can absorb water over 10 % (Brydson 1999). Lower moisture uptake is due to longer carbon chains of PA 410. Raw materials for PA 410 are sebacic acid and 1,4-diaminobutane (DAB), whose carbon atom content are 10 and 4, respectively.

Currently, the producer of PA 410 is a Dutch company DSM. PA 410 is ranked as high performance plastics (see Figure 2) and it is currently used in applications which require special mechanical properties or chemical and thermal resistance. PA 410 has generally better chemical resistance than the PA 66. PA 410 crystallizes fast which provides short cycle times in moulding. (Mittal 2012) (Kabasci & Stevens 2013)

PA 410 and other PAs are reinforced with glass and carbon fibre. GF reinforced grades are used in applications with high operational temperatures. In addition to heat resistance, reinforcing improves mechanical properties. Especially carbon fibre reinforced grades have great stiffness. The study by Kuciel (2012) showed that properties of PAs are possible to improve with bio-based flax fibre. Completely bio-based composite is formed, if fully bio-based PA, for example PA 11, is reinforced with flax fibre. However, the flax fibre reinforcing does not provide as good mechanical properties as GF reinforcing.

The production flow chart of the PA 410 production is shown in Figure 26. PA 410 is produced by a condensation of sebacic acid and the salt of DAB and. PA 410 contains 62 % bio-based carbon (DSM 2014). The bio-based content comes from sebacic acid, which is normally produced from castor oil (Brydson 1999). The petroleum-based raw material is DAB, which is also known as putresciene. DAB is hydrogenated from succinonitrile but it is possible to produce it from bio-based materials such as succinic acid or sugars (Harmsen 2014) (Qian et al. 2009). Currently, industrial scale production of succinonitrile is based on acrylonitrile and hydrogen cyanide. Succinonitrile is also produced from bio-based materials such as glutamic acid and glutamine. However, bio-based processes for DAB or succinonitrile are not yet ready for industrial scale production (Lammens et al. 2011) (Qian et al. 2009).

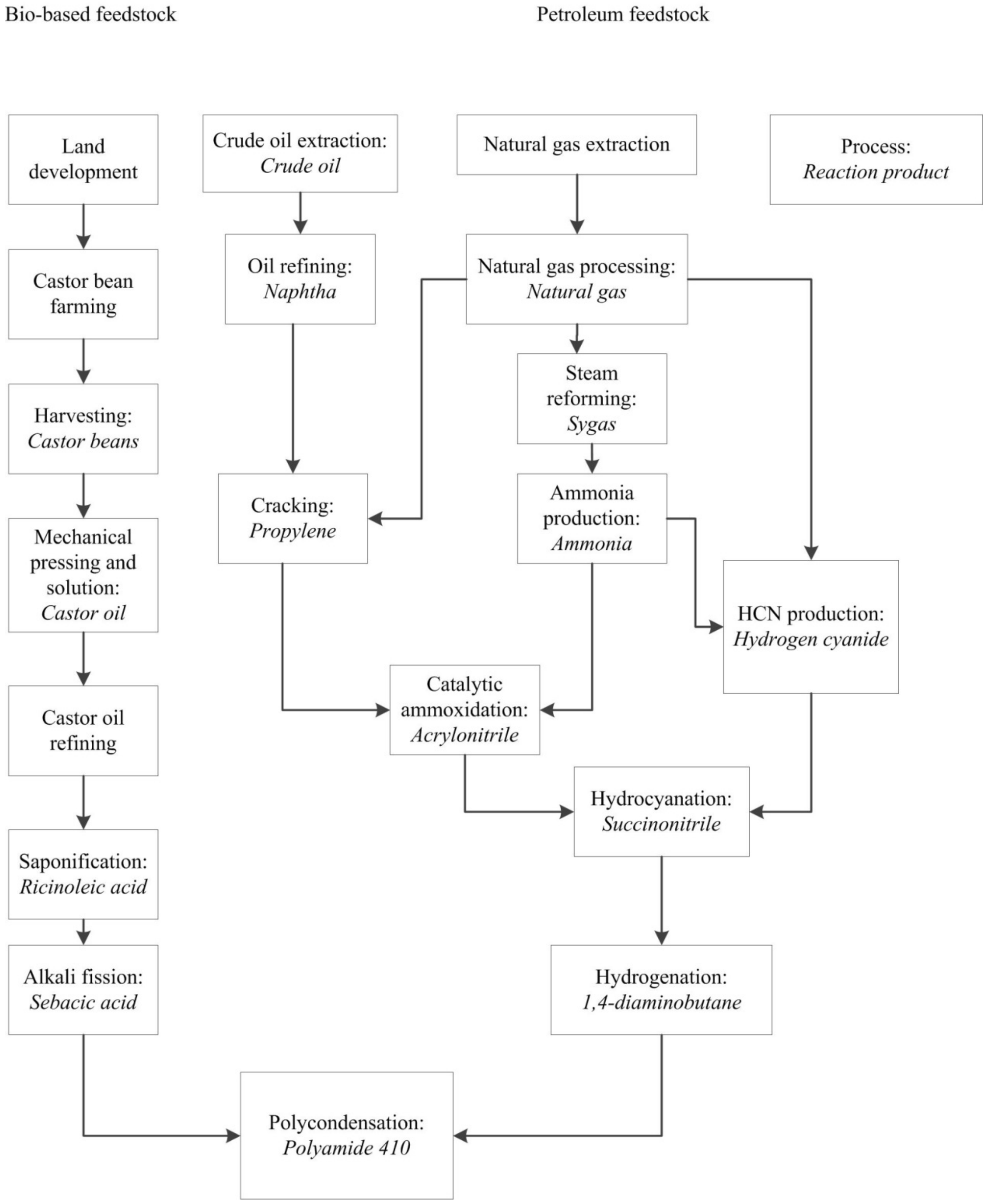

Figure 26. The production of PA 410 from partly bio-based raw materials. The production chain of the bio-based feedstock is modelled according to (Kabasci & Stevens 2013). The petroleum-based feedstock is modelled according to (Lammens et al. 2011) and (PlasticsEurope 2014).

10 EXPERIMENTAL

Materials suitability for the use in a base station was evaluated with material tests and LCA according to SFS-EN ISO 14040 and 14044 (2006) standards. The material tests provided information about the properties of the material. For the testing, the materials were injection moulded into existing front and rear cover moulds, and moulded covers were used as test specimens. Essential requirements of a plastic cover of base stations are shown in Figure 27.

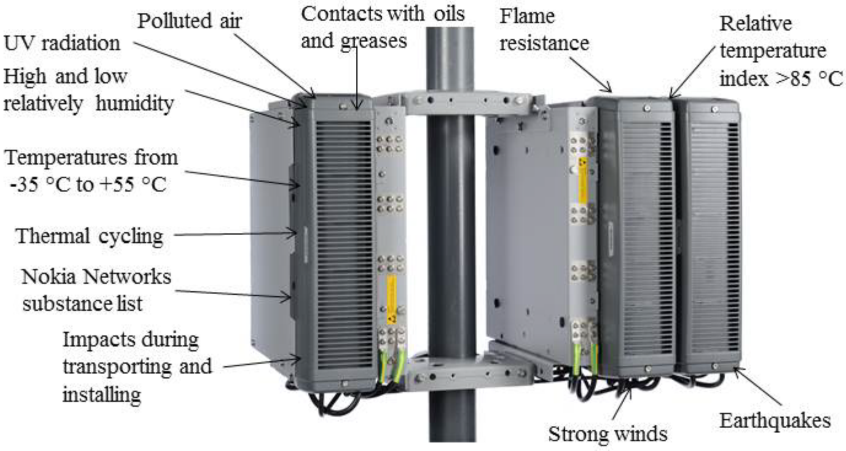

Figure 27. Essential requirements and constrains for plastic materials of base stations.

Radios and other electric devices are also restricted with many standards and guidelines. The materials in base stations must follow global material constraints such as Nokia Networks Substance List (Nokia Networks 2014b). Material properties are tested according to GR-487 CORE (2013), GR-63 CORE (2012) and many other standards. All polymer materials must have at least V1 flame retardant grade and their relative temperature index (RTI) must be higher than 85 °C. Every required material test was not included in the test programme of the studied materials. The purpose of the material test was to study, whether some of these materials were unusable in base station products. The selected tests are shown in Table 2.

Table 2. A list of the conducted tests, testing standards and the purpose of each test.

Test	Standard	Tested property
85/85 accelerated aging	-	Aging at 85 °C and 85 % RH
Chemical exposure	GR-487 CORE (2013)	Resistance against various chemicals
Change of temperature	-	The effect of CTE mismatch between plastics and aluminium.
Water absorption	SFS-EN ISO 62 (2008)	Mass and dimension changes due to water absorption
Outdoor exposure		Visual changes of plastics in real operating environments.

11 MATERIAL TESTING

11.1 Materials selection

Materials for the tests were provided by different suppliers. The reference material was virgin PC that is currently used in the covers. Suppliers and materials are shown in Table 3. Material properties are shown in Table 4.

Table 3. Materials and suppliers

Supplier	Trade name	Material grade	Material type
Bayer MaterialScience	Makroblend EC405 GR	PC/PET blend	Virgin PC + recycled PET
Bayer MaterialScience	Makrolon 6485 GR	PC	Virgin PC + recycled PC
DSM Engineering Plastics	EcoPaXX Q-07286	PA 410	Partly bio-based PA 410
DuPont de Nemours International	Sorona 3015 G	PTT + GF	Glass filled partly bio-based PTT
L&T Muoviportti Oy	-	PC	Recycled PC
Mitsubishi Engineering-Plastics Corporation	Xantar FC22UR	PC	Virgin PC
Rondo Plast AB	-	PC	Recycled PC

Table 4. Properties of selected materials. Properties of recycled PCs from L&T and Rondo were not available. Data are derived from Campus (2014), Bayer MaterialScience (2014), DuPont (2014d) and DSM (2014). Flame resistance is according to UL 94 (1.5 mm specimen) and the deflection temperature according to ISO 75 (test pressure 1.8 MPa).

	Xantar	Makrolon	Makroblend	Sorona	EcoPaXX
Young's modulus (GPa)	2.3	2.4	2.8	6.5	3.5
Yield stress (MPa)	60	60	65	125	75
Yield strain (%)	6	6	4	3	5.5
Charpy impact strength, 23 °C (kJ/m^2)	No break	No break	No break	25	60
Density (kg/m^3)	1200	1200	1240	1400	1150
Flame resistance	V-0	V-0	V-0	HB	V-2
Deflection temperature (°C)	130	124	78	200	110
Recycled material content (%)	0	30	30	0	0
Bio-based material content (%)	0	0	0	31	70

Mechanically recycled granulates from Rondo and L&T are pre-consumer grade materials. PC scrap from L&T is collected from Finland, but the origin of the material is unknown. L&T and Rondo do not provide specific information about the materials' properties. According to the L&T, only density, humidity and melt volume flow rate are measured from the recycled PC (Tuomisaari 2014). The melt volume flow rate is 9 cm^3/10 min which is approximately the same as those of a medium viscosity virgin PC and rPC from Bayer MaterialScience. Recycled materials from L&T and Rondo are not V-1 flame resistance graded. The recycled PC from L&T and Rondo was mixed with Xantar virgin PC from Mitsubishi Engineering - Plastics Corporation (MEP).

Makrolon from Bayer MaterialScience is a blend of virgin and recycled PC. Recycled material content is 30 %. The origin of the recycled material is post-consumer water containers, which are familiar in many offices. Makrolon is produced in China (Silvennoinen 2014). Makroblend supplied by Bayer MaterialScience is a blend of virgin PC and post-consumer PET from beverage bottles. Makroblend contains 30 % recycled material. The bio-based plastics are supplied by DuPont and DSM. Sorona from DuPont is a thermoplastic composite, which contains 15 % GF. The matrix is PTT, which contains bio-based PDO made from corn. Sorona is produced in the USA. FR Sorona was not available for testing. EcoPaXX from DSM is PA 410, which contains 70 % bio-based material from castor oil. Castor oil is produced in India and PA 410 is produced in Netherlands. DSM is currently the only producer for PA 410 (Kabasci & Stevens 2013).

11.2 Moulding of the samples

The purpose of the moulding was to evaluate, if rPC can be used in current moulds without changes. The bio-based plastics were moulded into same moulds. Their mouldability cannot be compared to those of PC, since they are different kinds of plastics and the mould was not designed for them.

Moulds of rear and front covers of Flexi Multiradio 10 Base Station were used for the injection moulding trials. The rear covers were moulded with Kraus Maffei KM250 moulding machine and front covers were moulded with Engel 300 moulding machine. 12 - 25 covers from each material were moulded. Test specimens and colour per material type are shown in Table 5. Plastic granulates were mostly coloured by the producers. "Naturally coloured" indicates that additional pigments were not used so these materials were bright. Black and green versions of PC/rPET were moulded. The black PC/rPET was coloured by Bayer. The green version was coloured during moulding by adding 2 % of green pigment in naturally coloured PC/rPET resin. Similarly, the red rPC100 was coloured during moulding by adding 2 % of red pigment in grey PC resin.

Table 5. The specimens and colours per material type.

Supplier	Sample ID	Colour	Count of front covers	Count of rear covers
DSM	PA410	Natural	23	12
Bayer	PC/rPET	Black	25	14
Bayer	PC/rPET	Green	17	18
DuPont	PTT	Natural	23	12
MEP + L&T/Rondo	rPC10	Grey	25	25
MEP + L&T/Rondo	rPC30	Grey	25	25
Bayer	rPC30B	Black	25	14
MEP + L&T/Rondo	rPC65	Dark grey	25	25
MEP + Rondo	rPC100	Black	0	25
MEP + L&T	rPC100	Red	14	25

Moulding parameters of front and rear covers are shown in Table 6 and Table 7, respectively. Moulded front and rear covers are shown in Figure 28 and Figure 29. The dwell time, heater and nozzle temperatures are expressed as ranges and the values were measured from several locations. The material was injected into mould in 4 locations. Mould temperature is an average of rear and front mould temperatures.

Table 6. Moulding parameters for injection moulding of front covers. The moulding machine was Engel 300. The dwell time, heater and nozzle temperatures were measured from several locations.

Sample	Injection pressure (bar)	Injection time (s)	Cooling time (s)	Heater temp. (°C)	Nozzle temp. (°C)	Mould temp. (°C)
PA410	650	3.6	36	265 - 280	280	77.5
PC/PET	1180	3.0	40	265 - 280	280 - 290	67.5
PTT	1010	3.6	42	260 - 285	260	92.5
rPC10	1830	3.4	35	280 - 295	290	82.5
rPC30B	1830	3.6	32	280 - 300	295 - 305	82.5
rPC30	1800	3.4	35	280 - 295	290	82.5
rPC65	1750	3.4	35	280 - 295	290	82.5
rPC100	1600	3.4	35	280 - 295	290	82.5

Table 7. Moulding parameters for rear covers. The moulding machine was Kraus Maffei KM250. The dwell time, heater and nozzle temperatures were measured from several locations.

Sample	Injection pressure (bar)	Injection time (s)	Cooling time (s)	Heater temp. (°C)	Nozzle temp. (°C)	Mould temp. (°C)
PC/PET	1280	2	42	250 - 315	290	69
rPC10	2150	3.1	32	280 - 315	310	89
rPC30B	2100	3	32	280 - 315	310	89
rPC30	2050	2.7	32	280 - 315	310	89
rPC65	1760	2.2	32	280 - 315	310	89
rPC100	1590	2.2	32	280 - 315	310	89

Figure 28. Samples of front covers. Upper row from left to right: rPC 100, rPC 65, rPC 30, rPC 10 and vPC. Lower row from left to right: PC/rPET (green), PC/rPET (black), PA 410, PTT GF and rPC 30B.

Figure 29. Samples of rear cover. Upper row from left to right: rPC 100 (red), rPC 100 (black), rPC 65, rPC 30, rPC 10 and vPC. Lower row from left to right: PC/rPET (green), PC/rPET (black), PA 410, PTT GF and rPC 30B.

11.3 85/85 accelerated aging

In 85/85 accelerated aging testing, materials are exposed to 85 °C and 85 % relative humidity for 2 000 h. Test is originally designed for testing integrated circuits. Test can also be used to study how materials behave at high temperatures and high relative humidity (RH). It must be taken into account that covers or solar shields of the base stations are rarely exposed to as extreme conditions.

Test was performed in the ARCTEST weather chamber. 2 rear covers of each material were tested. The covers were hung on the copper wires. The test chamber and test configuration are shown in Figure 30. The other cover was in the test chamber for 2 000 h. The other was removed and returned to the chamber for measurements every 500 h.

The samples were checked visually, weighed and dimensions were measured during and after the test. The covers were weighed with Kern CX B scale. Dimensions were measured with analogue slide gauge from 4 locations: length and width from the both sides of the cover. Changes of the appearance, mass and dimensions of the samples are compared to those of vPC.

Figure 30. Test chamber for 85/85 accelerated aging test. 2 rear covers of each material were exposed to 85 °C and 85 % RH for 2 000 h.

11.4 Chemical exposure

Chemical exposure was conducted according to GR-487-CORE (2013) standard. In this test, front covers were exposed to various chemicals. The standard requires that 10 different chemicals shall be used in the test. Due to the limited number of test specimens all the chemicals were not tested. In addition, each cover was treated with two chemicals. Because of the large size of the specimens, different chemicals were not in direct contact with each other. Selected chemicals were:

- 3 vol-% sulphuric acid
- Raid insect spray
- CRC bike oil (water displacement lubricant)
- WD40 water displacement lubricant
- 0.2 N NaOH.

Chemicals and their active substances are listed in Table 8. The expression 0.2 N is an abbreviation for 0.2 Normality. 0.2 Normality NaOH solution contains 0.2 equivalent gram weight NaOH in a litre of solution. 1 equivalent gram weight of NaOH is 40 g. Raid, CRC bike oil and WD40 were sprayed on the surface of the covers. Sulphuric acid and NaOH were rubbed on the surface with a cotton plug. The test configuration and containers are shown in Figure 31 and Figure 32.

Table 8. Substances for chemical exposure.

Chemical	**Active substances**
Insect spray (Raid House & Garden)	Pyrethrin, piperonyl butoxide
Lubricant (WD 40 multiuse aerosol)	Petroleum-based oil, aliphatic hydrocarbon, CO_2
Lubricant (CRC bike oil)	Petroleum-based oil, kerosene, CO_2, sulfonic acid
3 % sulphuric acid	Sulphuric acid
0.2 N NaOH solution	Sodium hydroxide

Figure 31. Configuration of the chemical testing: exposure by spraying and rubbing with cotton plug. Exposure times were 15 - 20 s.

Figure 32. Exposed front covers in plastic containers. The containers were sealed with duct tape and the covers were kept in containers for 30 days.

After the treatment, the specimens were placed in closed containers for 30 days at room temperature, approximately 20 °C. GR-487-CORE (2013) standard does not specify the test temperature. The containers were sealed with duct tape. After 30 days, the specimens were rinsed with water and they were visually checked for defects such as cracking, stripping or colour changes. Visual inspection was made with digital camera and Leica WILD M420 microscope. The objective magnifications were 5.8 – 35x. Locations of the photographed areas are shown in Figure 33. All covers were photographed at least from two locations even if material changes were not observed. These areas contain complex shapes, which may contain internal stresses. Internal stresses and chemical can together cause cracking or other defects.

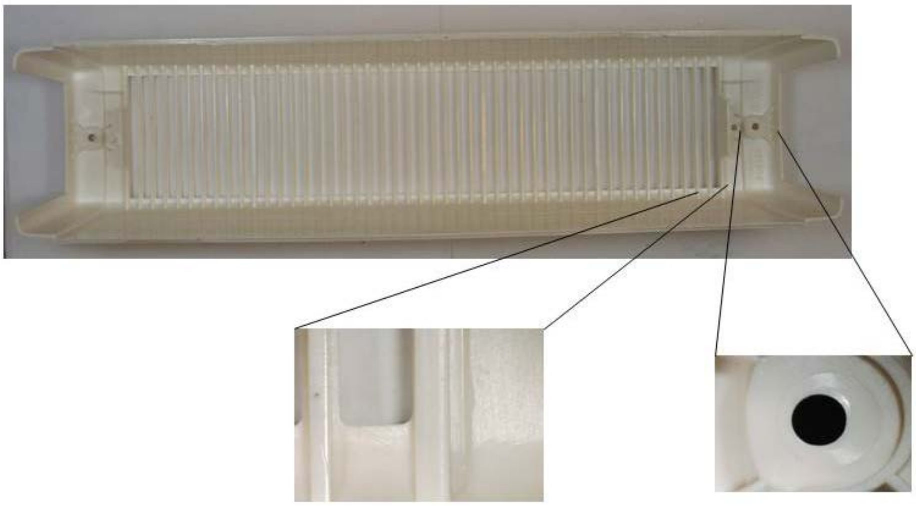

Figure 33. Locations which were photographed from all specimen.

In addition to visual inspection, specimens were inspected with Fourier transform infrared (FT IR) spectroscopy. IR spectra are used to distinguish different structures in the plastics. Different organic groups are identified from the absorbance or transmittance peaks. If chemical exposure has formed new compounds or degraded polymer chains, changes can be seen in the IR spectrum. The samples were studied with Thermo Scientific Nicolet iS10 FT IR spectrometer. The attenuated total reflection (ATR) technique was used since it can reveal surface defects. Deeper surface defects must be analyses with other methods. IR spectra were obtained from 16 consecutive scans with a resolution of 4 cm^{-1}. The spectrum wave number range was 500 - 4000 cm^{-1}, which corresponds to wavelengths of 2.5 - 20 µm. The principle of FTIR spectroscopy is shown in Figure 34. Small specimens were cut from the covers with side cutters for FT IR spectrometer. The specimens were wiped with swipes containing methanol and ethanol to remove the residual chemicals from the surface. A specimen and spectrometer are shown in Figure 35.

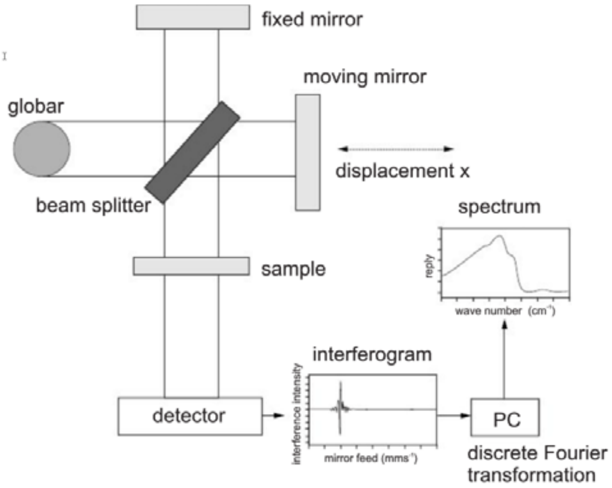

Figure 34. The principle of FTIR spectrometry. The ATR technique was used to analyse the results of chemical testing. (Grellmann & Seidler 2007)

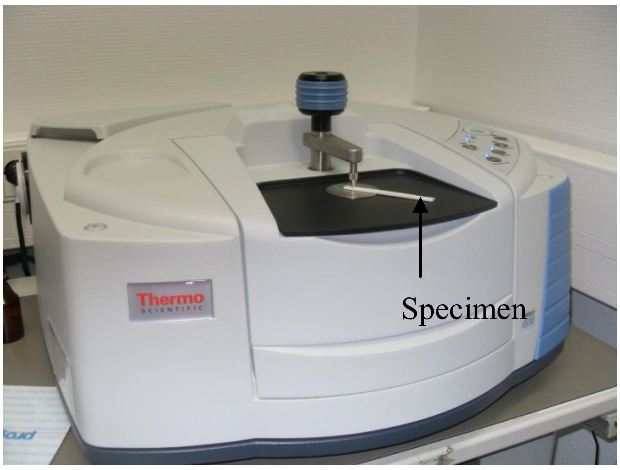

Figure 35. FT IR spectrometer and a white specimen cut from the cover.

11.5 Outdoor exposure

Front covers were used as specimens in outdoor exposure. The purpose of this test was to evaluate how recycled and bio-based plastics tolerate real operating environments. Testing was conducted in four locations: in Finland (Oulu and Espoo), in Greece (Athens) and Kenya (Nairobi). These locations were selected, because their weather conditions differ greatly. In Finland, samples were subjected to humid and relatively mild climate. Maximum temperatures in Finland were approximately 30 °C. Conditions in Greece were warmer and drier than those in Finland. (Reliable Prognosis 2014) UV radiation in Greece is also higher (TEMIS 2014). Test site in Athens was located near industrial area, so the air contains probably more impurities than that of Finland. The conditions in Kenya were combination of Finland and Greece. Temperatures and average humidity were similar than those in Finland. However, temperatures in Finland decreased after the summer. UV radiation in Kenya was even higher than that in Greece (WHO 2014), because Kenya is located in an equatorial region. Due to the location the conditions in Kenya are similar throughout the year.

2 covers of each material were tested in every location. Covers were placed on open locations such as on rooftops, where they are exposed to sun, heat, rain and pollution. Weather data for the tests was provided by Reliable Prognosis (2014) and Tropospheric Emission Monitoring Internet Service (TEMIS 2014). The data is collected in Appendix 7. Maximum, minimum and average values of temperature, humidity and total UV-dose are shown in Table 9. UV dose of Nairobi was not available. Based on UV indices, the UV dose is significantly higher than that in Athens.

Table 9. Weather statistics from test sites. Complete data is shown in Appendix 7. Data is provided by Reliable Prognosis (2014), TEMIS (2014) and WHO (2014). UV indices and doses which represent Espoo and Oulu are measured in Jokioinen and Sodankylä, respectively.

	Athens	**Espoo**	**Nairobi**	**Oulu**
Temperature (°C)				
Max	40.0	30.8	30.0	31.1
Min	7.0	-4.5	9.0	-14.8
Average	21.9	12.2	19.7	9.7
Relative humidity (%)				
Max	100.0	100.0	99	100.0
Min	10.0	31.0	20.0	26.0
Average	59.1	82.6	68.8	82.5
UV index				
Max	11.2	5.4	12	4.7
Min	1.6	0.2	11	0.0
Average	6.4	2.9	11.7	2.1
UV dose (kJ/m2)				
Total	570	259	-	224

The front covers were attached vertically on the test rack in Finland and Greece. In Kenya, the covers were positioned horizontally to maximize the UV-dose. Test configurations in Finland, Kenya and Greece are shown in Figure 36. The test racks were constructed from wood and covers were attached on the racks with cable ties. In many outdoor tests 45 °C tilting angle is used (Masters & Bond 1999), but in this case the vertical position was selected. The covers are also vertically positioned in most radio sites. A single cover from each location was sent for examinations after 6 months. The other cover was left on the rack for further testing.

a)

b)

c)

d)

Figure 36. Test racks in a) Athens, b) Espoo, c) Nairobi and d) Oulu.

11.6 Water absorption

Water absorption was performed by applying SFS-EN ISO 62 (Plastics. Determination of water absorption) (2008) standard. Test specimens were rear covers and small plastic plates cut from the covers. Testing was conducted by immersing the covers in deionized water at room temperature (approximately 23 °C).

11.6.1 Mass change

Mass change of plastics was measured with small plastic plates. Covers were not used, since the surface water is necessary to remove before weighing, but it is difficult for a complex product such as plastic covers. Weighing of immersed covers can roughly show how much water is absorbed. Inaccuracy in the measurement is significant because the water absorption of the PC is low (Megat-Yusoff et al. 2013). Droplets on the surface can significantly affect results. Therefore the exact mass change due to water absorption was studied with small plastic samples cut from the covers. Weight, length and thickness of samples were 70, 80 and 3 mm, respectively. The samples were dried at 58 °C for 90 h in convection oven. The samples were weighed with Mettler Toledo Delta Range scale before and during the drying. Accuracy of the scale was 0.1 mg.

Figure 37. The weighing of a sample during the water absorption testing. The weighing was performed before and after drying and during the test until equilibrium was reached.

After drying samples were immersed in plastic containers containing deionized water. Containers were placed in room temperature (23 °C). Samples were weighed first after 24 h and then after 5 days. Following measurements were performed at week's interval until equilibrium was reached. Surface water was removed with paper towel every time before weighing. Weighing was performed within 1 min after the sample was removed from the container.

11.6.2 Dimension changes

Dimension changes due to water absorption were studied with rear covers made of virgin and recycled PC. The purpose was to study whether the dimensions of the cover stay within tolerances, when the cover has absorbed water. Bio-based plastics were not included in the measuring, because their dimensions differed significantly from those of the PC covers.

The covers were dried at 39 °C for 4 h in Heraeus Vötsch K884 climate chamber. Covers were weighed with Mettler Toledo PB8001 scale before and during the drying process in order to see when they were dried. Accuracy of the scale was 0.1 g. After drying covers were immersed in separate plastic containers containing deionized water. Each container contained approximately 10 l water. Covers were weighed before the test and every 24 h. The surface water was removed from the covers with paper towels and compressed air. Weighing was performed within 5 min after removing the cover from the container. After the saturation, dimensions of the rear covers were measured with Mitutoyo EURO C-A9166 coordinate measuring machine. Dimensions of the immersed covers were compared with dry covers. Dimensions were measured from 4 locations: hole distance and width at 3 locations (both ends and in the middle). Measured dimensions are shown in Figure 40.

Figure 38. Drying and weighing of rear covers for the water absorption test. The covers were dried at 39 °C for 4 h. The covers were weighed before and after drying and every 24 h during the immersion.

Figure 39. Immersion of rear covers. Plastic containers were filled with deionized water.

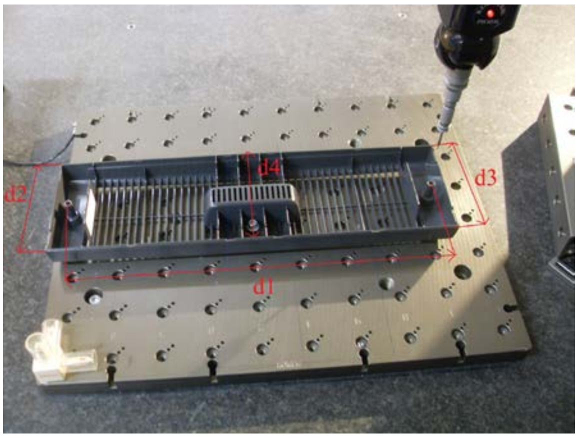

Figure 40. 3D measurement of rear covers. Measured dimensions were d1 (hole distance), d2 and d3 (width at the ends) and d4 (width at the middle).

11.7 Change of temperature

Base stations are subjected to temperature gradients which can cause deformation into parts. Different coefficients of thermal expansion can result in fractures or loosening of joints. If screws are loosened, there is a risk that parts fall from the poles or masts. That cannot be allowed, since base stations are located in public areas.

Rear covers were used to test how recycled and bio-based plastics can tolerate temperature cycling. The covers were attached into AlCu frames with 2 Torx T25 stainless steel screws. The test configuration is shown in Figure 41. The frames and screws are similar to those that are used in the real products. Screws were tightened with 2.5 Nm using torque screwdriver (torque range 0.5 - 5 Nm). Tightening torque was selected according to the product assembly manual. All studied materials were tested except PA 410. PA 410 rear covers were shrunk significantly in moulding so the covers could not be attached into the aluminium frame.

Figure 41. The test configuration for change of temperature test in Vötsch VC^3 7018 climate chamber.

-35 °C and 55 °C were selected for minimum and maximum temperatures, respectively. Temperature change rate was 2 °C/min. Temperature was held for 1 h at minimum and maximum. Test cycle was started and ended at 25 °C. Total duration of the test was 145 cycles (501.5 h). One temperature cycle is illustrated in Figure 42. Test was performed in Vötsch VC^3 7018 climate chamber. After the test, the screws were opened with torque wrench and the opening torque was reported.

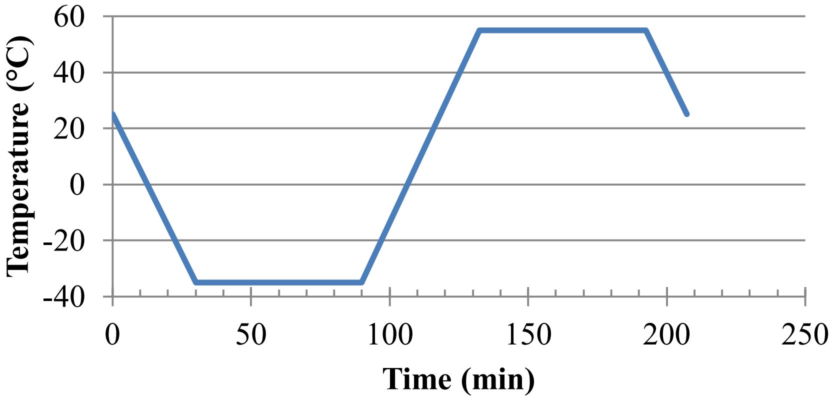

Figure 42. A temperature cycle in the change of temperature test. Test consisted of 145 cycles. Temperature change rate was 2 °C/min and min and max temperatures were -35 °C and 55 °C, respectively. Temperatures were selected according to the product requirements.

12 LIFE CYCLE ASSESSMENT

12.1 Goal and scope definition

12.1.1 Goal

LCA tool is used to study environmental burden of recycled and bio-based plastics. It is wanted to understand, how large environmental impacts are related to production and processing of recycled and bio-based plastics. Suitability of LCA to compare those materials is also evaluated.

12.1.2 Scope of the study

Functional unit is 1 kg of plastic granulate at the factory gate. This study contains material production from raw materials to polymers and plastics. The production flame retardants and other additives are not included. The compounding of the additives and the plastic granulate is, however, included.

Impact categories in this study are climate change and primary energy demand. These impact categories were selected because they are widely accepted and understood. Primary energy demand contains energy derived from fossil fuel and non-fossil fuel resources. Climate change estimated with global warming potentials (GWP 100) according to IPCC 2013 and GHG Protocol. Results are presented as midpoint indicators.

12.1.3 Types and sources of data

Primary data from material producers and secondary data from databases were used. Ecoinvent 2.2 (2014) was used to model transports, electricity and heat production and production of additional substances that are required for processes. Data for petroleum-based polymers and plastics were derived from eco-profiles of PlasticsEurope (2014). Data for recycling processes were estimated with literature and derived from material suppliers and manufacturer of the recycling equipment. The exact data sources are listed in Life Cycle Inventory analysis in Chapter 12.2. Life Cycle Inventory analysis and impact calculations were conducted with GaBi 6 LCA software (PE International 2014a).

Geographical scope of the data depends on the material. Material options are shown in Table 10. vPC, PC/rPET and PA 410 are produced in Europe. German electricity mix is assumed for PET recycling process and compounding of PA 410. Italian electricity mix is used for PC/rPET compounding. Electricity mixes for rPC models are Finland and China. Pre-consumer recycled PC is processed in Finland and post-consumer PC in China. USA specific electricity mix is used for the production of PTT GF. European electricity mix is used to estimate the impacts of TPA and GF production. Energy sources of electricity supply mixes of selected countries are shown in Appendix 2.

Table 10. Studied materials and material blends. Geographical scope is used to select specific electricity mixes.

Material	Compound	Geographical scope
Virgin PC	100 % vPC	Europe
Pre-consumer rPC	10, 30, 65 and 100 % rPC + vPC	Finland + Europe
Post-consumer rPC	30 % rPC + 70 % vPC	China + Europe
PC/rPET	30 % rPET + 70 % vPC	Italy + Europe
PA 410	70 % bio-based sebacic acid + 30 % DAB	Europe
PTT GF	31 % bio-based PDO + 54 % TPA+ 15 % GF	USA + Europe

12.1.4 System boundaries

A Cradle to Gate approach is applied in the study. The processes which are directly related to material production are included, such as collection, sorting, transporting, granulating and compounding. Recovery and recycling of PET and PC scrap is included in the production of partly recycled PC and PC/rPET blend. Cut-off approach was used to model recycling, therefore the first life of the plastics waste is not considered. Raw material and intermediate requirements of each scenario are collected in Table 11, Table 12, Table 13 and Table 14. The collection of PC waste is efficient, because pre-consumer waste is sorted already at the place of origin. Post-consumer PC waste is derived from office water bottles and sorting and collection of these is efficient. On the other hand, PET bottle waste is assumed to contain other plastics in cap and labels, for example. The raw material requirements of PA 410 and PTT GF are based on chemical balance.

Table 11. Mass (kg) of raw materials and intermediates for vPC and rPC scenarios.

Raw material / intermediate	vPC	rPC 10	rPC 30	rPC 30B	rPC 65	rPC 100
Virgin PC	1.00	0.90	0.70	0.70	0.35	0.00
PC waste	0.00	0.10	0.30	0.30	0.65	1.00

Table 12. Mass (kg) of raw materials and intermediates for PC/rPET scenario. 0.41 kg PET bottle waste is required for 0.30 kg PET granulates. The bottle waste contains also PE and other plastic waste.

Raw material / intermediate	PC/rPET
Virgin PC	0.70
Baled PET bottles waste	0.41
PET granulate	*0.30*
Other plastic waste	*0.08*
PE waste	*0.03*

Table 13. Mass (kg) of raw materials and intermediates for 1 kg of PA 410 granulate. The estimation is based on the chemical balance. Hydrogen cyanide and acrylonitrile are intermediates of the 1,4-diaminobutane production.

Raw material / intermediate	**PA 410**
Sebacic acid	795.09
1,4-diaminobutane	346.55
Hydrogen cyanide	*106.25*
Acrylonitrile	*208.61*

Table 14. Mass (kg) of raw materials and intermediates for 1 kg of PTT GF granulate. The estimation is based on the chemical balance. Starch is an intermediate for the PDO production and TPA and PDO are intermediates of PTT.

Raw material / intermediate	**PTT GF**
Glass fibre	0.15
Polytrimethylene terephthalate	0.85
TPA	*0.68*
PDO	*0.31*
Starch	*0.35*

Electricity and heat consumption and transport distances for processes were collected or estimated. Transport types and distances in kilometres are show in Table 15. Transport of the materials was calculated in tonne kilometres (tkm), which is calculated by multiplying the weight of the product (in tonnes) with the distance (in km). The fuel production was also taken into account. Transportation from the plastics producer or compounder to the moulding is not included.

Table 15. Transportation scenarios. The impacts of transportation were not specified in the dataset of vPC and PA 410, since the data was derived directly from PlasticsEurope (2014) and PE International (2014b)

Material	Distance (km)	Transport type
Virgin PC	Included in the dataset	
Pre-consumer PC	300 (Waste collection) 800 (vPC from Germany to Finland) 200 (From reprocessing to compounding)	Lorry 16 - 32 t (EURO 5)
	1 000 (vPC from Germany to Finland)	Freight ship
Post-consumer PC	300 (Waste collection) 45 (Waste sorting prior recycling) 500 (rPC and vPC from reprocessing to compounding	Lorry 16 - 32 t (EURO 5)
Post-consumer PET	177 (Waste collection and sorting 500 (vPC and rPET from Germany to Italy for compounding)	Lorry 16 - 32 t (EURO 5)
PA 410	Included in the dataset	
PTT GF	300 (GF transporting) 425 (Starch transporting)	Lorry 16 - 32 t (EURO 5) Rail freight

Injection moulding and the use phase are neglected from calculations since it is assumed that they are similar for each material. Materials are estimated to be equally durable so that life time of the product is independent of the material. End-of-life calculations are not included due to the cut-off approach. They shall be taken into account at the next life of the material. Assumptions for the end-of-life are that vPC, rPCs, PC/rPET and PA410 are recycled and used for similar application. Glass filled PTT is incinerated and glass fibre is used as filling material for constructions (Lauttia 2014).

12.2 Life cycle inventory analysis

Data sources are listed in Table 16, Table 17 and Table 18. Detailed information for the plastics processing modules are shown in Table 19. The dataset for PDO fermentation was based on fermentation of ethanol from sugar cane. Sugar cane was changed to maize starch and ethanol was changed to PDO. The ratio between starch and PDO was calculated. Based on the chemical balance, 1.12 kg maize starch is required to produce 1 kg PDO and 0.314 kg PDO is required for 1 kg of 15 % GF reinforced PTT.

Table 16. The database data used in life cycle primary energy demand and GWP calculations. The module of PDO fermentation was based on the fermentation of ethanol from sugar cane. Data sources are Ecoinvent 2.2 (2014), PlasticsEurope (2014) and PE International (2014b)

Module name	**Source**	**Name of the dataset**
Electricity, China	Ecoinvent 2.2	CN: Electricity, low voltage, at grid [supply mix]
Electricity, Finland	Ecoinvent 2.2	FI: Electricity, low voltage, at grid [supply mix]
Electricity, Germany	Ecoinvent 2.2	DE: Electricity, low voltage, at grid [supply mix].
Electricity, Italy	Ecoinvent 2.2	IT: Electricity, low voltage, at grid [supply mix]
Glass fibre	Ecoinvent 2.2	RER: Glass fibre, at plant
Heat from diesel	Ecoinvent 2.2	CH: Heat, at cogen 200 kWe diesel SCR, allocation energy [cogeneration]
Heat from natural gas	Ecoinvent 2.2	RER: Heat, natural gas, at boiler modulating <100 kW [heating systems]
Maize starch production	Ecoinvent 2.2	DE: maize starch, at plant
PA 410	PE International	EU-27: Biopolyamide (PA) 4.10 granulate (castor based) (sebacic acid average)
PDO fermentation	Ecoinvent 2.2	BR: ethanol, 95 % in H_2O, from sugar beets, at fermentation plant (modified)
Polycarbonate	PlasticsEurope	RER: Polycarbonate
Sodium hydroxide	Ecoinvent 2.2	RER: Sodium hydroxide, 50 % in H20, production mix
Sulphuric acid	Ecoinvent 2.2	RER: Sulphuric acid, liquid, at plant
Terephthalatic acid	PlasticsEurope	RER: Purified terephthalatic acid, at plant
Transport by lorry	Ecoinvent 2.2	RER: Transport, lorry 16 - 32t, EURO5 [Street]
Transport by rail	Ecoinvent 2.2	RER: transport, freight, rail [Railway]
Transport by ship	Ecoinvent 2.2	OCE: transport, transoceanic freight ship [Water]

Table 17. Literature data used in life cycle primary energy demand and GWP calculations.

Module name	**Source**	**Name of the dataset**
rPET pellet extrusion	Kent (2008) & Shen et al. (2011)	DE: PET pellet production
Shredding of PET bottles	Shen et al. (2011)	DE: Plastics waste to PET flakes
Compaction and sorting of plastics waste	Perugini et al. (2005)	DE: PET waste compaction and sorting CN: PC waste compaction and sorting

Table 18. Data from material suppliers and recycling equipment manufacturers.

Module name	**Source**	**Name of the dataset**
Recycling of PC	Tuomisaari (2014)	FI: Reprocessing of PC waste CN: Reprocessing of PC waste
Solid-state condensation	Albert (2014)	DE: Solid-state condensation of PET
Polycondensation of PTT	Albert (2014)	US: Polycondensation of PTT

Table 19. Data for plastics processing modules. Data is derived and estimated from literature or provided by manufacturers. Compounding and extrusion of plastics is estimated according to Albert (2014) and Kent (2008).

Module	**Electricity consumption (kWh/kg)**	**Heat consumption (MJ/kg)**	**Transport by lorry (tkm)**	**Other**
Compounding of PC in Finland/China	0.389	0.252	0.200	-
Compounding of PC/PET in Italy	0.389	0.252	0.500	-
Recycling of PC	0.222	-	0.300	-
Solid-state condensation of PET	0.140	-	-	-
Compaction and sorting of plastics waste	0.105	0.150	0.045	-
Shredding of PET bottles	0.077	2.500	0.132	0.06 kg 50 % NaOH 0.06 kg H_2SO_4
rPET pellet extrusion	0.389	0.252	-	-
Polycondensation of PTT	0.140	-	-	-
Compounding of PTT and GF	0.389	0.252	0.045	
Compounding of PA 410	0.389	0.252		

Life cycle inventory tables are presented in Appendix 1. Inventory tables contain energy resources and GHG emissions to air. Process flow charts made with GaBi 6 are shown in Appendix 3.

13 RESULTS AND ANALYSIS OF MATERIAL TESTING

13.1 Accelerated aging test

13.1.1 Visual changes

Significant colour changes were observed in PA 410 and PC/rPET. PTT covers also changed slightly colour. PA 410 and PTT did not contain colouring additives which explains partly the colour changes. The colour change of PA 410 is related to the moisture absorption. Polyamides are susceptible to absorb more water than PC, PET or PTT, and colour change in PA 410 was largest. Visual changes in PA410 are showed in Figure 43. The colour of the cover changed gradually from white to orange.

Figure 43. The colour change in PA410 in the accelerated aging testing. Photos were taken with digital camera after 0 (on left), 500, 1 000, 1 500 and 2 000 h.

PC/rPET cover showed also significant visual changes, which were not limited to colour changes. Green PC/rPET covers were fractured after 1500 h and the black versions also shown significant deformation. The PC/rPET covers were clearly bent already after 190 h as showed in Figure 44. Bending of the covers already at the beginning of the test is due to low deflection temperature of PC/rPET. At 85 °C, PC/rPET became soft and relatively large weight of the cover was enough to cause deformation. T_g of the PET is also at the same temperature range. Mechanical properties are generally weak near T_g (Seppälä 2005).

Some bubbles were also formed on the surface of the covers as shown in Figure 45. Gases were trapped inside material during moulding. When temperature was increased, gases were expanded which caused bubbling. Bubbles were formed in the middle of the side of the cover. Middle part of the cover was also deformed most because cover was supported only from the ends. After 190 h, black PC/rPET covers were moved from the copper wires to flat surface. The black covers were flattened within 24 hours after the move. The green PC/rPET covers were kept on the wires.

The fractured covers are shown in Figure 46 and Figure 47. A black PC/rPET cover was fractured because pieces of the green cover were dropped onto it. The second fractured cover was dropped onto a red PC cover which was not damaged. Both green PC/rPET covers were fractured almost at the same time. Fractures were observed after 1 500 and 1 530 h from the beginning of the test. Other PC/rPET covers were not fractured during the test, because they were well supported. However, they were badly deformed.

Figure 44. The deformation in PC/rPET covers after 190 h in the accelerated aging testing. The grey cover on the left is reference cover made from vPC.

Figure 45. Bubble formation in PC/rPET covers in the accelerated aging testing after 190 h. Gas was trapped inside the material during moulding. When temperature was increased gases expanded which caused bubbling.

Figure 46. Fractured PC/rPET covers. The cover on the left fractured after 1500 h and the cover on the right fractured after 1530 h.

Figure 47. Fractured green and black PC/rPET covers. The green cover (on the left) was dropped onto the black cover (on the right), which fractured due to the impact.

Some colour changes were observed in PC/rPET. A grey material layer was formed on the PC/rPET covers. The dimensions and mass were also reduced. The reason for the change is different than that for PA410. The colour change of PC/rPET is related to the hydrolysis and degradation of the material, not only to the moisture absorption. The colour change of the PC/rPET cover is shown in Figure 48. The shortening of the cover is shown in Figure 49.

Figure 48. The colour change in a PC/rPET cover. Photos were taken with digital camera after 0 (on left), 500, 1 000, 1 500 and 2 000 h. Grey material layer formed on the surface after 1 500 h.

Figure 49. Deformation in the PC/rPET cover after 1500 h in accelerated aging testing. The black PC/rPET cover above was deformed due to hydrolysis. Below is a green PC/rPET cover which was not exposed to the test conditions.

Based on this test, mechanical properties of PC/rPET are not maintained at 85 °C and 85 % RH. Mechanical tests were not performed but the material was extremely brittle. Samples from the PC/rPET were also studied with FT IR spectrometer to analyse whether material composition was changed. The IR spectra of fractured and untested samples are shown in Figure 50. Most of the peaks in the IR spectra are at same places. This indicates that same functional groups are detected in both materials. Absorbance levels are different but the height of the peaks is affected by measuring conditions. Clear differences are noticed at 3 300 cm^{-1} and 1 600 cm^{-1}. The peak at 3 300 cm^{-1} most probably comes from an alcohol which is formed due to the hydrolysis. Hydrolysis at 85 °C causes degradation of PET into its starting materials. One of the starting materials for PET is ethylene glycol. Figure 51 shows comparison of PC/rPET spectra and ethylene glycol. The highest peak in the lowest spectrum is at the same area as the new peak in PC/rPET 1 500 h spectrum. The hydrolysis caused polymer chain scission which makes the material brittle. Hydrolysis affects also on the other sample materials, but not at the same rate.

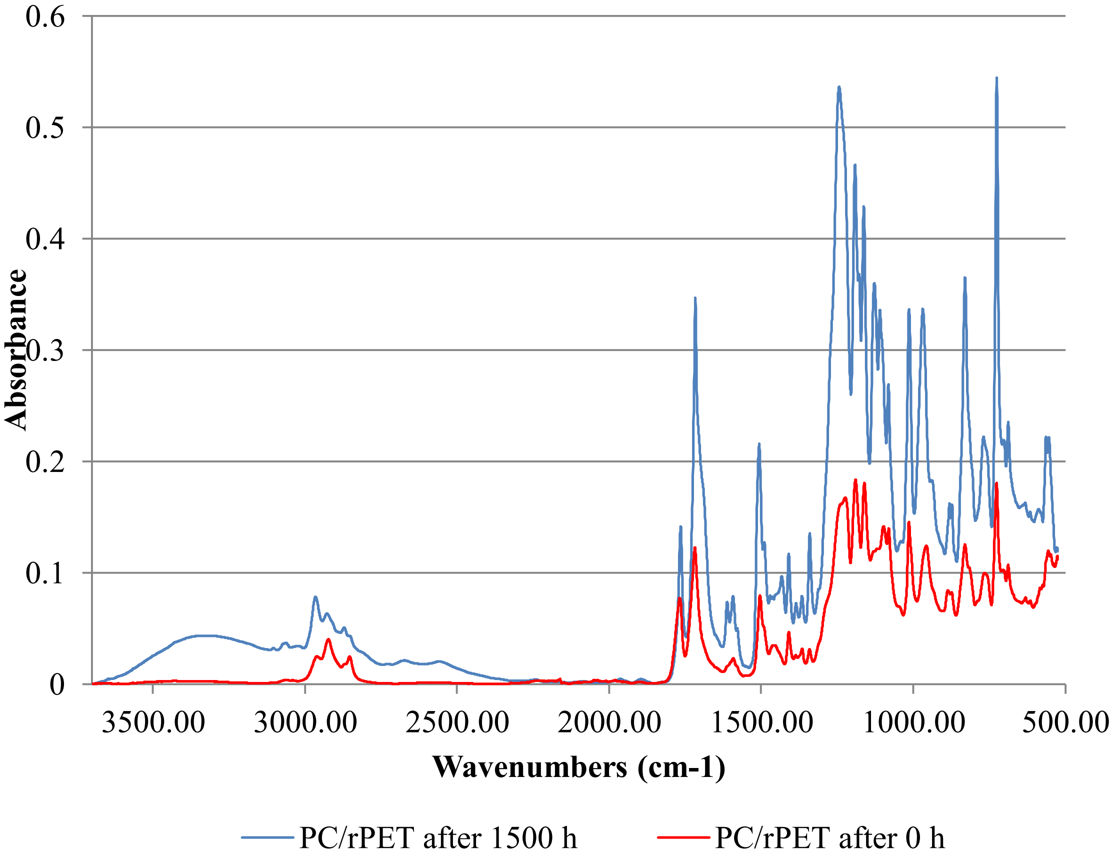

Figure 50. FT IR spectra of PC/rPET samples in the accelerated aging testing. The resolution was 4 cm^{-1} and 16 scans were performed with ATR technique. Red line is from an untested sample. Blue line is from fractured material.

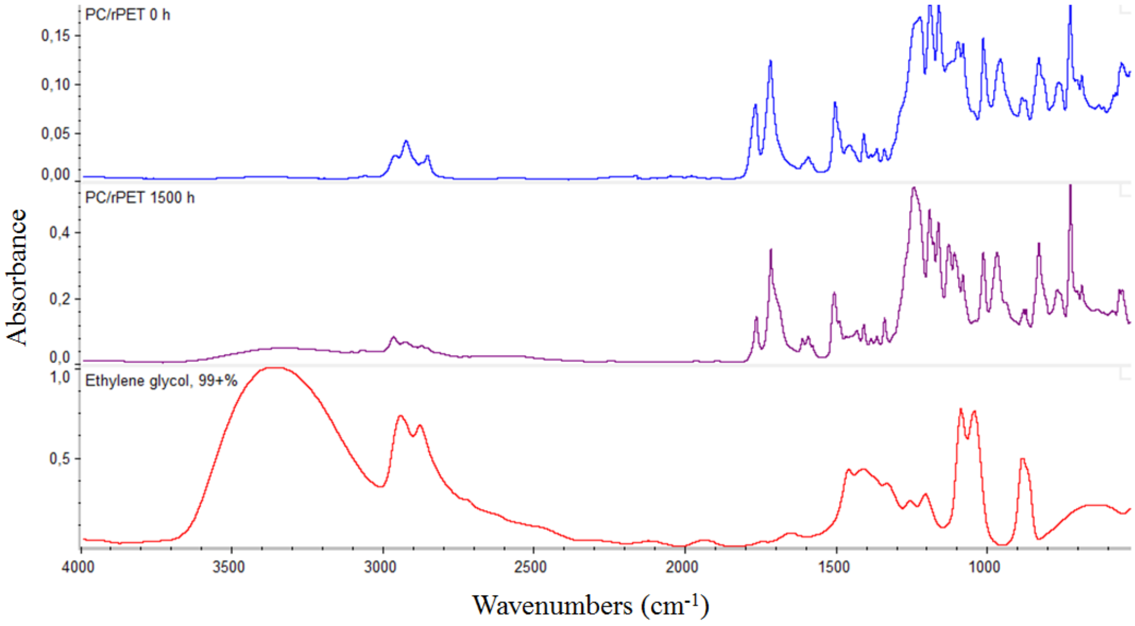

Figure 51. IR spectra of test samples and ethylene glycol. Ethylene glycol is a starting material for PET. The peak at 3350 cm^{-1} in PC/rPET after 1 500 h comes from ethylene glycol which is formed due to hydrolysis.

Colour changes in PTT covers were hard to distinguish. The covers in the aging test became slightly brighter than untested specimen. The difference was possibly to see when both samples were side by side like in Figure 52. Mechanical properties were not degraded as much as those of PC/rPET. After the test, PTT cover felt slightly more brittle than the untested cover. The cover was significantly more ductile than PC/rPET cover after the test. An impact test should be applied to evaluate the brittleness of the material.

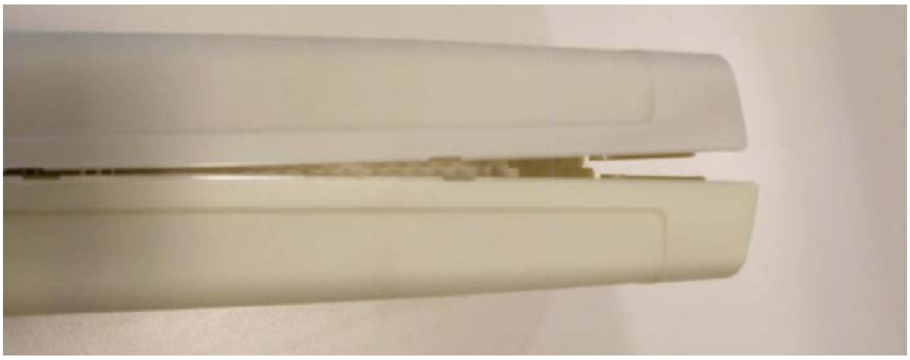

Figure 52. A PTT sample after the accelerated aging testing. The material became slightly brighter in the test. The cover above is tested in 85/85 conditions. The cover below is an untested sample.

The covers made from PC did not suffer visual degradation. Both virgin and recycled versions maintained their appearances. Dark colours of the covers made the analysing difficult. Possible surface defects are not found as easily as from brighter covers. The mechanical properties were not degraded as much as those of PTT or PC/rPET. Recycled material content did not affect the performance of the cover. Photos of rPC samples are collected in Appendix 4.

13.1.2 Mass and dimension changes

Masses of the covers before, during and after the test are shown in Table 20. Covers were weighed every 500 h during the test. Dimension changes in the test are shown in Table 21 and Table 22. The greatest mass changes occurred in the PA 410 and PC/rPET covers. Due to the hydrolysis, the mass of the PC/rPET cover was reduced 7.5 %. The mass of PA 410 covers were increased 3.7 % due to the water absorption. The mass increase of PA 410 covers did not cause notable dimension changes. The mass and dimension changes of PC covers were so small that they could not be perceived with the used measuring equipment.

Table 20. Mass change of the covers in the accelerated aging testing. Scale: Kern CX B. Complete data is shown in Appendix 4.

	Mass (g)		
Sample	**0 h**	**2000 h**	**Change**
PA410	245	254	3.7 %
PC/rPET	279	258	-7.5 %
PTT	317	320	1.0 %
rPC10	277	278	< 1 %
rPC30B	269	270	< 1 %
rPC30	277	278	< 1 %
rPC65	273	274	< 1 %
rPC100	270	271	< 1 %
vPC	269	270	< 1 %

Table 21. Dimension changes in the length in the accelerated aging testing. Samples were measured with a slide gauge. Results are averages from 2 samples.

	Length (mm)		
Sample	**0 h**	**2000 h**	**Change**
PA410	443.5	444.1	0.1 %
PC/rPET	446.2	427.7	-4.1 %
PTT	447.5	447.5	0.0 %
rPC10	445.3	445.3	0.0 %
rPC30B	445.2	445.0	0.0 %
rPC30	445.3	445.3	0.0 %
rPC65	445.4	445.2	0.0 %
rPC100	445.5	445.3	0.0 %
vPC	445.0	445.1	0.0 %

Table 22. Changes in the width in the accelerated aging testing. Measuring was performed with a slide gauge. Results are averages from 2 samples.

	Width (mm)		
Sample	**0 h**	**2000 h**	**Change**
PA410	124.8	125.1	0.3 %
PC/rPET	125.6	121.2	-4.8 %
PTT	125.8	125.7	0.0 %
rPC10	125.3	125.4	0.0 %
rPC30B	125.0	125.2	0.0 %
rPC30	125.3	125.3	0.0 %
rPC65	125.3	125.3	0.0 %
rPC100	125.3	125.4	0.0 %
vPC	125.3	125.3	0.0 %

13.2 Water absorption

Dimension changes due to the water absorption were tested with rear covers. The mass change was tested with specimens cut from the front covers. The cut specimens were immersed for 2300 - 3500 h. The immersion time depended on how fast the equilibrium was reached in the sample. The test was ended when the mass difference between two consecutive measurements was less than 0.1 mg. Mass change as a function of time is presented in Figure 53.

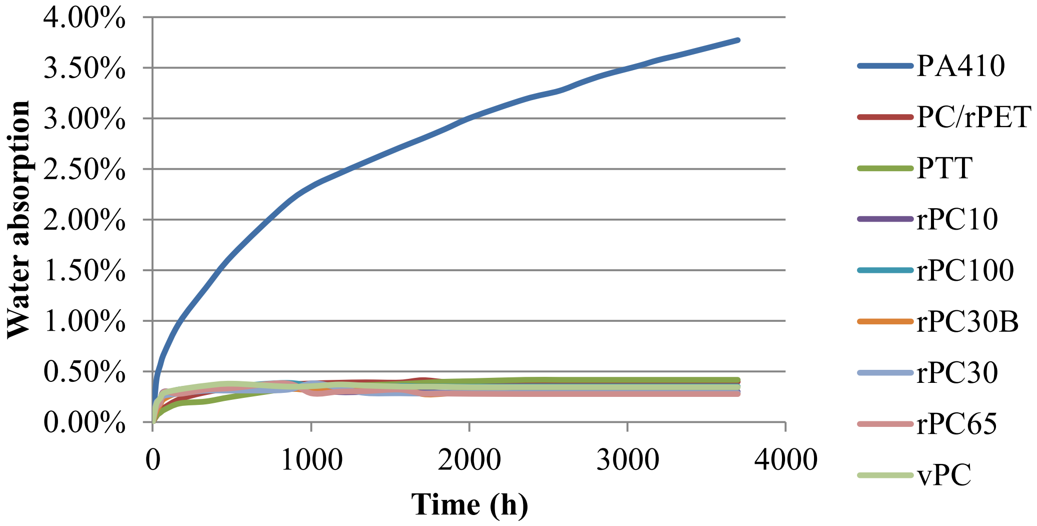

Figure 53. Mass change due to water absorption. 70 x 80 x 3 mm plaques were immersed in deionised water until the equilibrium was reached. Test was ended before PA 410 reached equilibrium.

Water absorption of PA 410 is considerably higher than that of other samples. More time was also required for the equilibrium. Water absorption of rPCs, vPC, PC/rPET and PTT is at the same level, 0.30 - 0.40 %. The water absorption rate of PCs was relatively fast. Approximately 80 - 100 % of the weight gain was already reached after 72 h. The recycled material content did not cause significant difference on the water absorption. The absorption rates of the PC/rPET and PTT were slower than those of PCs, but the absorptions at the equilibrium were higher than those of PCs. Weighing data is shown in Appendix 5.

Dimension changes of wet rPC and vPC rear covers were studied with a coordinate measuring device. Rear covers were immersed in water for 72 h prior measuring the dimensions. Measuring of the dimensions of PA 410, PTT GF and PC/rPET covers was ruled out due to slow water absorption rate. The water absorption of these covers did not reach equilibrium in sufficient time. Comparing the performance of PA 410, PTT GF and PC/rPET with PC covers would have been difficult, since the dimension of these covers differed significantly from those of PC covers already prior immersion. The difference of the dimensions can be seen, for example, in Table 26.

The vPC and rPC rear covers were weighed before, during and after the immersion. The mass change during the immersion is shown in Table 23. The mass change of the covers is greater than that of plaques due to droplets, which were trapped in the small corners in the cover. The change of dimensions before and after the immersion is presented in Table 24. Complete measuring data is collected in Appendix 5. Based on the measuring, vPC cover maintained its dimensions best. There is not a clear effect of the recycled material content on the dimension changes. For example, the cover containing 100 % recycled material maintained its dimensions better than the cover containing 65 % recycled material. In addition, the dimension changes of rPC 10 were similar to those of rPC 65. After all, the dimension changes were small. The hole distance of all samples changed less than 0.02 %. The dimensional stability of the screw hole distance is beneficial for rear covers since it prevents the stresses derived from a screw joint when attached to an aluminium frame. Width of the covers varied more and the change would be large for a part which is used for bearing or joining parts. The largest difference between dry and wet state was observed in the rPC 30. The width of the cover at the end and middle changed -0.65 % and 0.49 %, respectively. The large change was not consistent which indicates an error during measuring.

Table 23. Mass change of the rear covers in the water absorption test. Covers were immersed in deionised water at 23 °C.

			Mass (g)		
Sample	**0 h**	**24 h**	**48 h**	**72 h**	**Change**
rPC10	277.4	278.1	278.3	278.6	0.43 %
rPC30B	269.8	270.5	270.6	270.8	0.37 %
rPC30	277.3	278.1	278.3	278.4	0.40 %
rPC65	271.8	272.4	272.6	272.8	0.37 %
rPC100	269.8	270.6	270.7	271.0	0.44 %
vPC	271.8	272.3	272.5	272.7	0.33 %

Table 24. Dimension changes in the water absorption test. The specimens were measured in dry and wet conditions with Mitutoyo coordinate measuring device. Measuring data is presented in Appendix 5.

Sample	**Hole distance**	**Width: end 1**	**Width: end 2**	**Width: middle**
rPC10	0.01 %	0.34 %	0.06 %	0.35 %
rPC30 B	0.01 %	0.14 %	0.12 %	-0.05 %
rPC30	0.01 %	0.00 %	-0.65 %	0.49 %
rPC65	0.02 %	0.03 %	-0.25 %	-0.32 %
rPC100	0.01 %	-0.05 %	0.01 %	-0.12 %
vPC	0.01 %	-0.03 %	-0.01 %	0.03 %

13.3 Change of temperature

The loosening torques of the screws are presented in Table 25. The torque was measured with a torque wrench. Screws in PC/rPET cover were loosened significantly more than screws in other covers. Some loosening also occurred in PTT cover. Virgin PC cover maintained the tightening torque best. Differences in the dimensions and release of internal stresses can explain the loosening of screws. Table 26 shows the hole distance and diameter of the samples. The PTT and PC/rPET covers are the longest. GF reinforced PTT is stiffer than PC/rPET (Table 4) which may explain, why the screws of the PC/rPET cover were loosened more than those of PTT cover.

Table 25. Loosening torques of the cover screws. One cover was attached into an aluminium frame with two screws. The relative tightness indicates loosening torque in comparison to tightening torque (2.5 Nm). Results are average values.

Sample	Loosening torque (Nm)	Relative tightness
PC/rPET	<0.2	< 10 %
PTT	0.8	30 %
rPC10	1.3	50 %
rPC30B	1.3	50 %
rPC65	1.5	60 %
rPC100	1.5	60 %
vPC	1.8	70 %

Table 26. The hole distance and diameter (mm) of the samples. Measuring was done with Mitutoyo coordinate measuring device.

Material	Hole distance	Hole diameter
PC/rPET	410.304	5.49
PTT	411.473	5.54
rPC10	409.533	5.51
rPC30B	409.587	5.51
rPC30	409.539	5.50
rPC65	409.536	5.50
rPC100	409.603	5.51
vPC	409.611	5.08

13.4 Chemical exposure

13.4.1 Visual observation of the chemical exposure

Visual observations are collected in Table 27. Generally, chemicals did not cause notable damage into the materials. Some residual chemicals were found on the surface of the covers, but degradation was not observer after cleaning the surfaces. Photos of all exposed samples are collected in Appendix 6. All covers were photographed at least from 2 locations even if material changes were not observed. Colour changes in the photos are due to different exposure settings of the camera.

Table 27. Visual observations of the covers after chemical exposure.

Sample	**Insect spray**	**CRC**	**WD 40**	**Sulphuric acid**	**NaOH**
PA 410	Some dissolved material in the container	-	-	Red spots at the lower part of the cover	NaOH traces on the surface
PC/rPET	-	-	-	-	NaOH traces on the surface
PTT	-	-	-	-	NaOH traces on the surface
rPC10	Some dissolved material in the container	-	-	Bubbles or droplets on the surface	NaOH traces on the surface
rPC30B	-	-	-	-	NaOH traces on the surface
rPC30	-	-	-	Bubbles or droplets on the surface	NaOH traces on the surface
rPC65	-	-	-	Bubbles or droplets on the surface	NaOH traces on the surface
vPC	-	-	-	Bubbles or droplets on the surface	NaOH traces on the surface

- = no degradation or material changes

Macroscopic photos of the specimens did not show any cracking or delamination due to ESC. Light red spots were formed on the surface of the PA 410. The area in which the spots were formed contained also black spots from moulding. Black spots contain impurities which can react with sulphuric acid and cause the red spots.

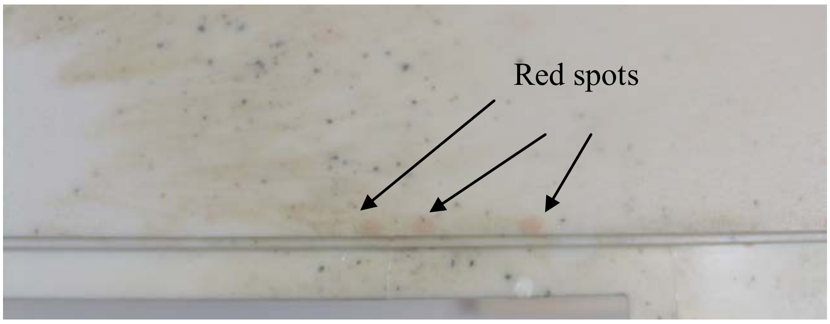

Figure 54. Red spots were formed on the PA410 during sulphuric acid exposure.

The covers exposed to lubricating oils did not suffer from visual changes. Insect spray dissolved some material from the container or from lower parts of rPC 10 and PA 410 covers. Residual material was observed in the bottom of the container. The rPC 10 and PA 410 covers which were exposed to insect spray did not show degradation from other areas. Side surfaces of the rPC 10 and PA 410 covers are shown in Figure 55. Insect spray flowed into the bottom of the container during the test. Therefore the lower parts of the covers were under insect spray for longer times than upper part of the cover. That may have caused the dissolving.

Figure 55. rPC 10 cover before (above) and after (below) insect spray and lubricating oil exposure. Insect spray (RAID) was sprayed on the left end of the cover.

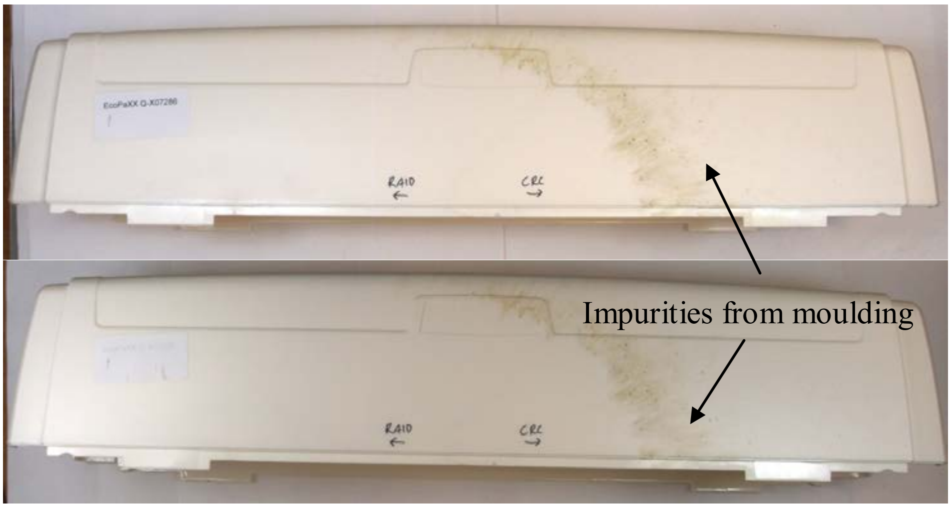

Figure 56. Surface of the PA 410 cover before (above) and after (below) insect spray and lubricating oil exposure. The dark impurities on the right side of the cover are not related to chemical exposure.

Residual NaOH was observed on the surface of all specimens after the test. NaOH layer was larger in PC and PC/rPET covers than that in PA 410 or PTT covers. Visual changes in the material under the NaOH were not observed. PC/rPET cover after NaOH exposure is shown in Figure 57. Used NaOH solution was so mild, only 40 g/l, that it did not cause visible degradation. Strong NaOH solutions can cause damage into plastic parts.

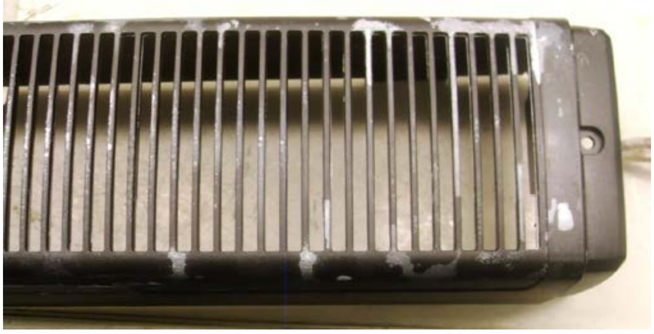

Figure 57. NaOH spots on the PC/rPET cover after the chemical test. Material under the NaOH layer was intact.

13.4.2 IR spectra

IR spectra of the samples were analysed to see whether the material composition was changed during the test. Each of the diagrams contains spectra from every chemical exposure. If changes in polymer chains were occurred during the test, the difference is easy to see. Spectra for the samples are shown in Figures 56 - 63.

The IR spectra of PA 410 in Figure 58 are similar. Peaks are not shifted significantly. Absorbance levels are different but that is explained by measuring uncertainties. The contact between sample and the probe may not be identical in every measurement.

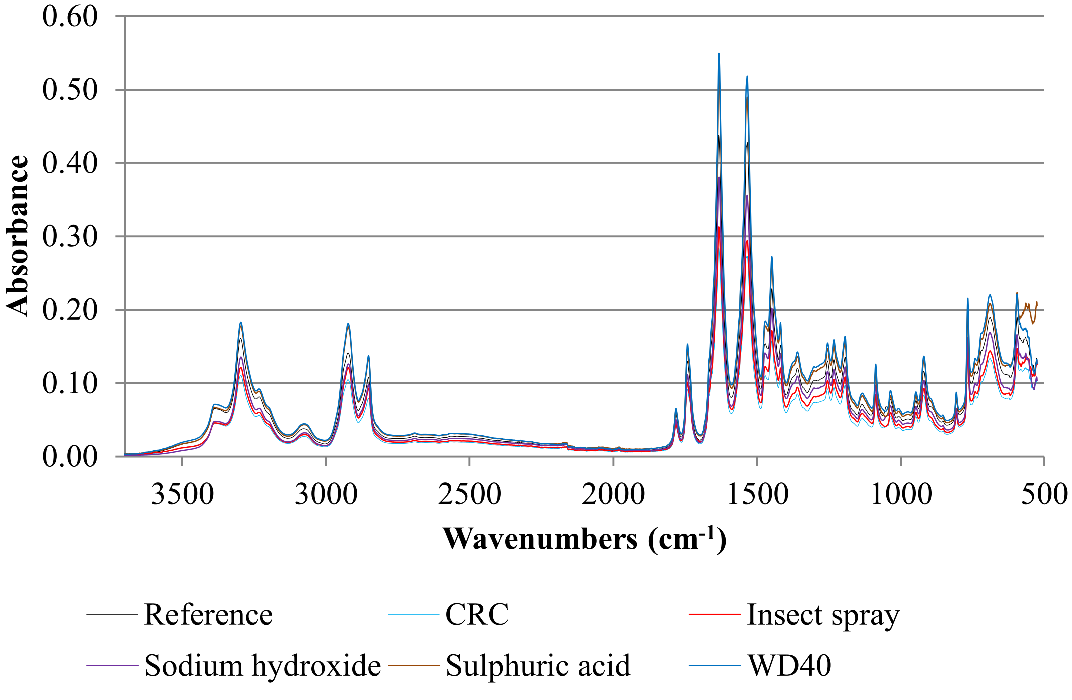

Figure 58. The IR spectra of PA 410 samples. The ATR technique was used with 16 consecutive scans. The resolution was 4 cm^{-1}.

Changes in PC/rPET cannot be seen in the IR spectra in Figure 59. The sample exposed to insect spray shows some difference in around 1300 cm^{-1}. The peak is not as sharp as those of the other samples.

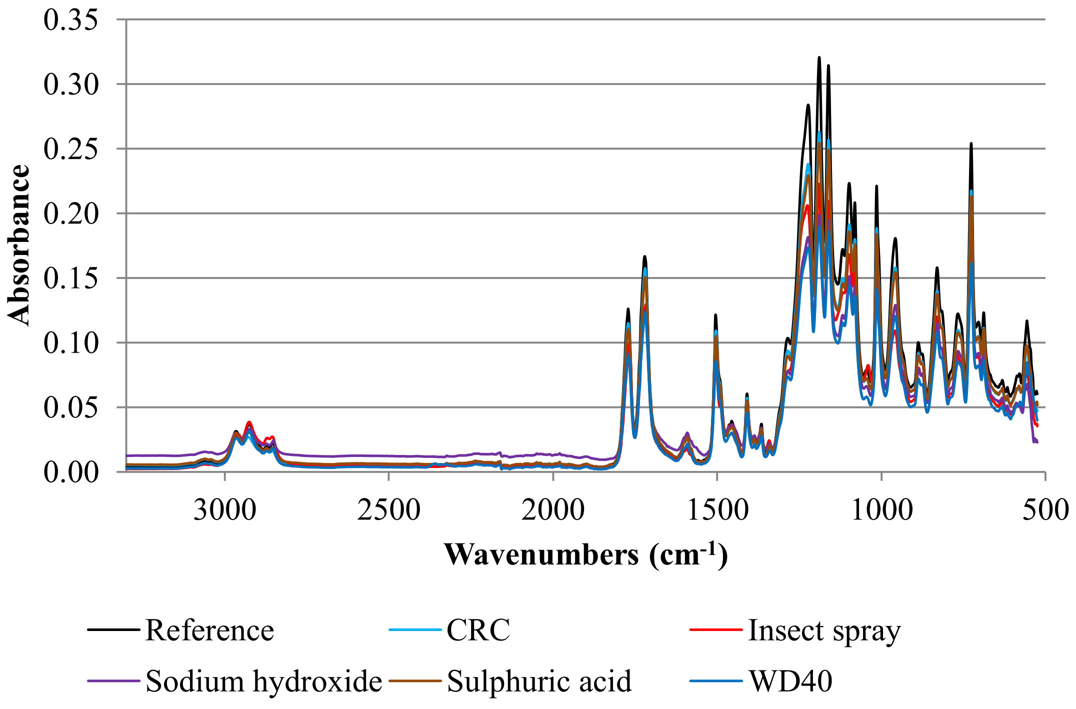

Figure 59. The IR spectra of PC/rPET samples. The ATR technique was used with 16 consecutive scans. The resolution was 4 cm^{-1}.

Any degradation of the polymer structure of PTT cannot be seen in the IR spectra in Figure 60. Peaks are uniform with a slight variation in absorbance.

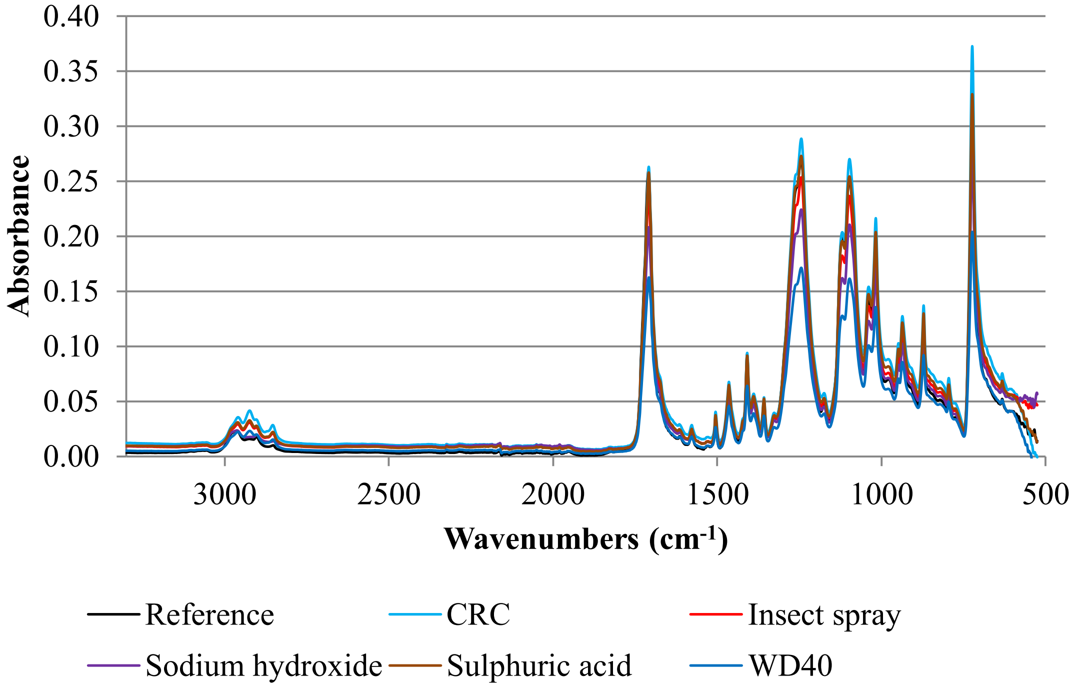

Figure 60. The IR Spectra of PTT samples. The ATR technique was used with 16 consecutive scans. The resolution was 4 cm^{-1}.

The IR spectra of PC are mostly similar. The samples exposed to sulphuric acid, lubricating oils and NaOH have similar spectra as the reference samples. The IR spectra of PCs exposed to insect spray show notable variation approximately in 1 040 and 1 800 cm^{-1}. Similar small peak or elevation is shown in all rPC and vPC samples. The spectra of rPC 10, rPC 30, rPC 30B, rPC 65 and vPC are shown in Figure 61, Figure 62, Figure 63, Figure 64 and Figure 65, respectively. The variations in the spectra are shown better in Figure 66. Material changes are not, however, as large as those of PC/rPET in accelerated aging test (Figure 50).

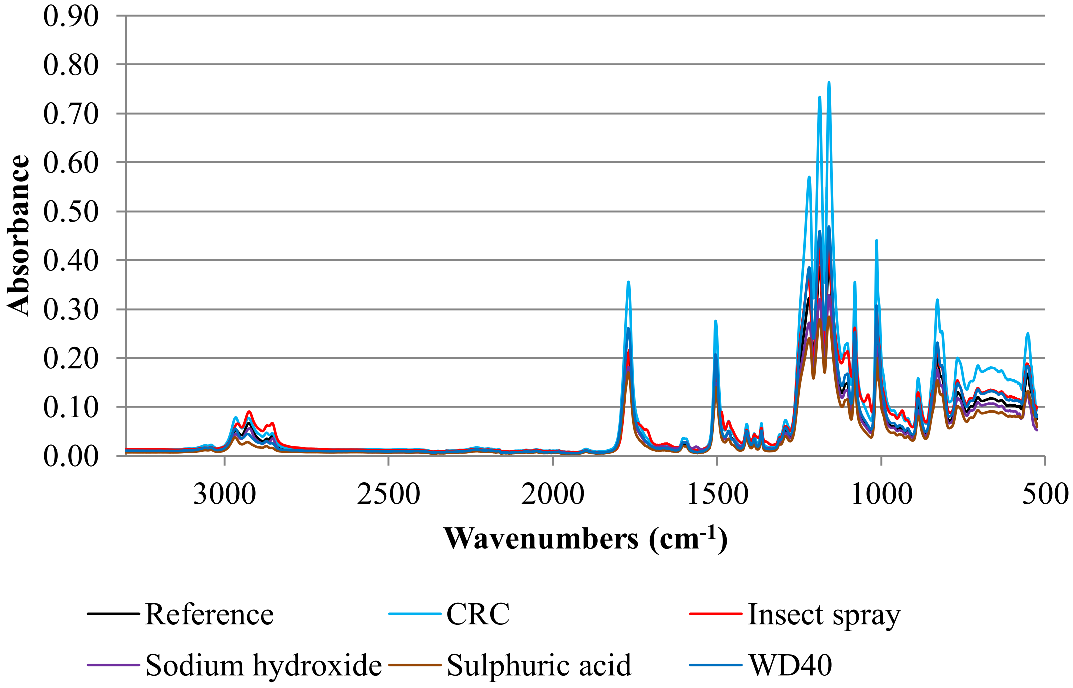

Figure 61. The IR spectra of rPC 10 samples. The ATR technique was used with 16 consecutive scans. The resolution was 4 cm^{-1}.

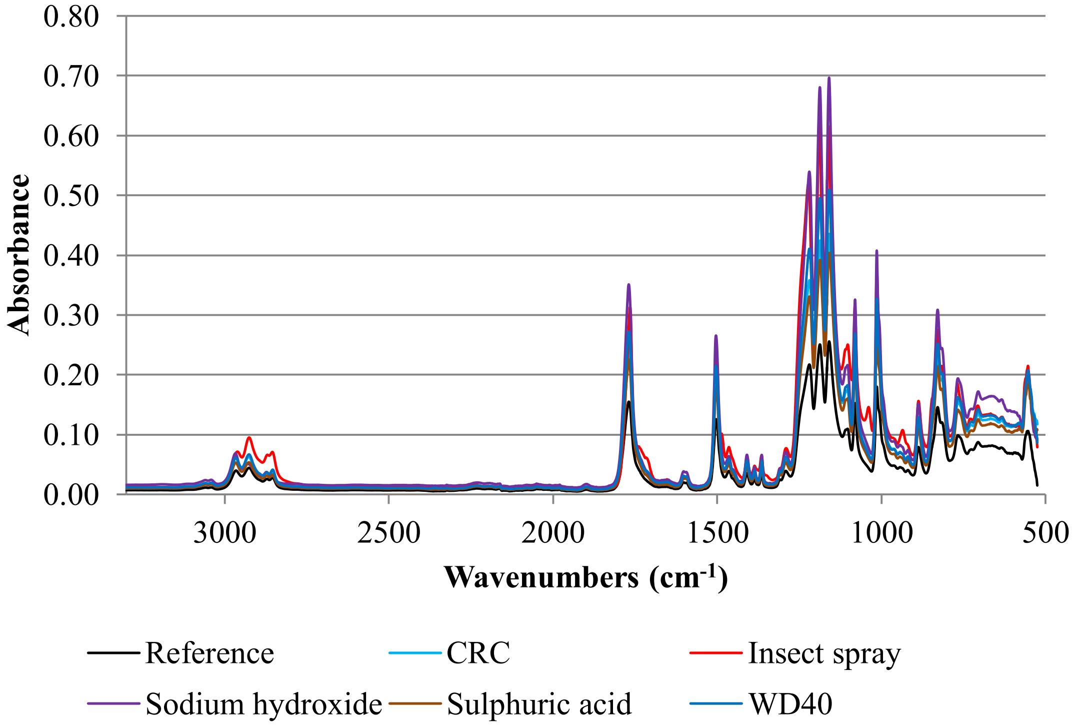

Figure 62. The IR spectra of rPC 30 samples. The ATR technique was used with 16 consecutive scans. The resolution was 4 cm^{-1}.

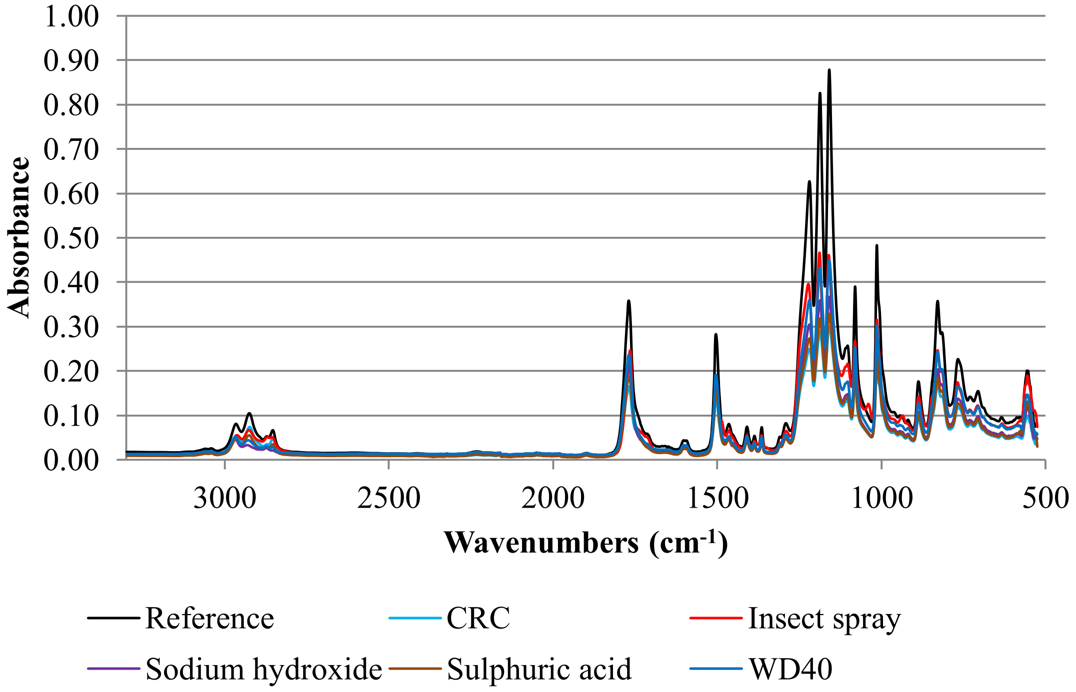

Figure 63. The IR spectra of rPC 30B samples. The ATR technique was used with 16 consecutive scans. The resolution was 4 cm^{-1}.

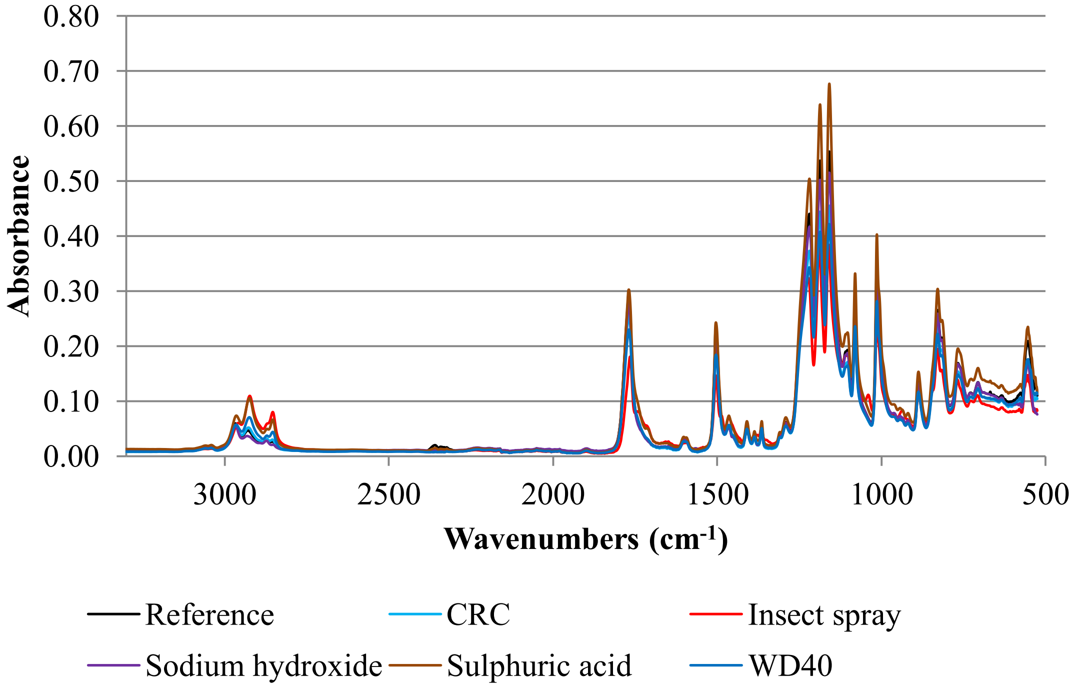

Figure 64. The IR spectra of rPC 65 samples. The ATR technique was used with 16 consecutive scans. The resolution was 4 cm^{-1}.

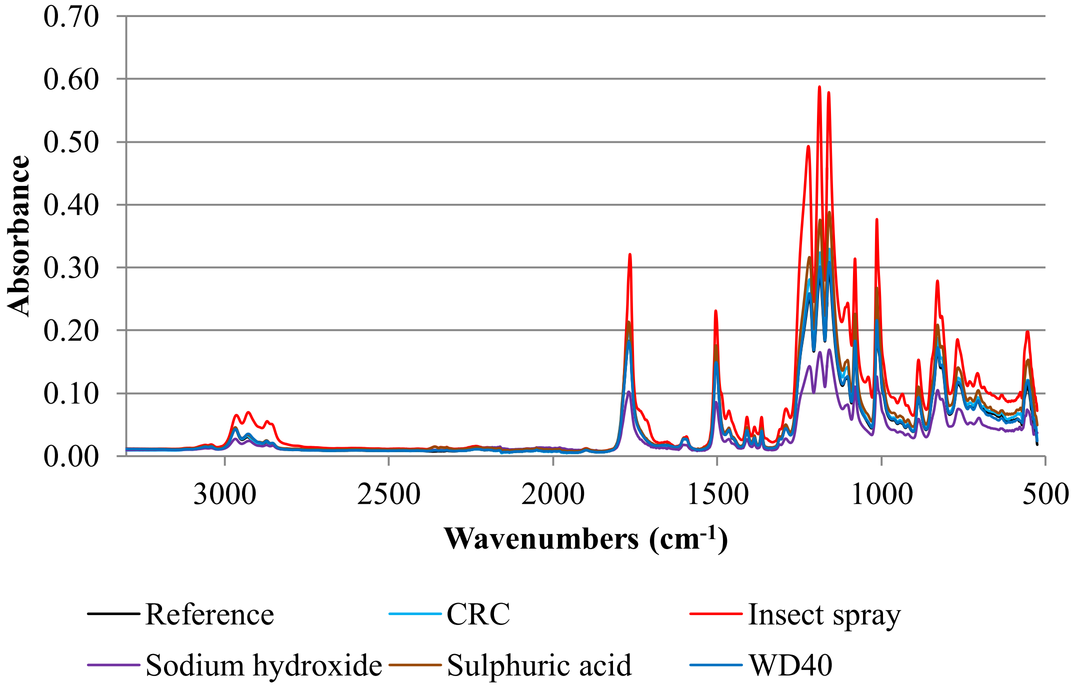

Figure 65. The IR spectra of vPC samples. The ATR technique was used with 16 consecutive scans. The resolution was 4 cm^{-1}.

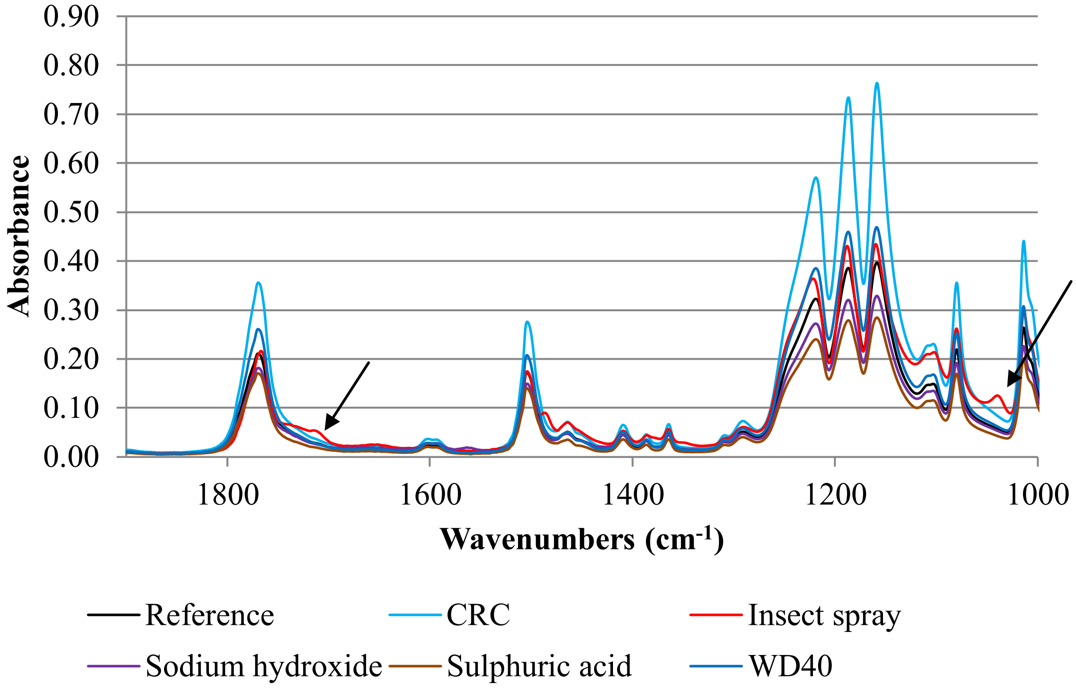

Figure 66. Cropped spectra of rPC 10. The arrows point at the additional peaks that are formed in the PC samples during insect spray exposure. Similar observations were made in every PC sample.

The additional peaks may originate from piperonyl butoxide, which is a component of the insect spray. A comparison between piperonyl butoxide, unexposed rPC 10 and rPC 10 exposed to insect spray is shown in Figure 67.

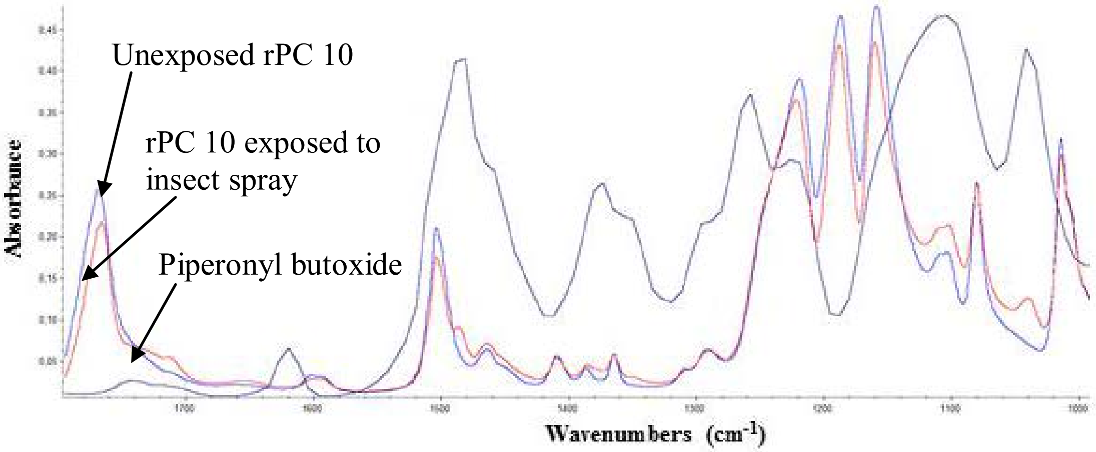

Figure 67. Spectra of rPC 10 in comparison to that of piperonyl butoxide. The spectrum of piperonyl butoxide shows clear peaks in 1 040 and 1 800 cm^{-1}.

The peaks from piperonyl butoxide not necessarily indicate material degradation. They may be from traces of insect spray. Colour changes or surface defects were not found in the visual inspection. However, insect spray affected strongest PCs, because similar additional peaks cannot be seen in the spectra of PA 410, PC/rPET and PTT. The peaks cannot be explained by impurities, because similar changes were observed in each PC grade.

13.5 Outdoor exposure

Plastics were tested in outdoor environment for 6 months in Finland, Greece and Kenya. Material performance in the exposure is evaluated visually. Results are presented in the figures below. Small differences are not easily distinguished in the pictures, but pictures show, how the overall appearance of the covers was affected by the outdoor environment. Generally, visual degradation was not observed during the exposure. For example, significant colour changes or cracking of the surface did not occur. Some dirt was observed in the tight corners and surface of the covers which is shown in Figure 68. The surface of the samples under the dirt layer was intact. Similar dirt traces were observed in every sample. However, the dirt was easier to distinguish from light coloured PA 410 and PTT covers. The dirt layers on the samples were thin, so the covers were not exposed to highly concentrated chemicals. Samples were located in relatively open places so wind and rain have easily cleaned most of the dirt.

Figure 68. Dirt on the surface of PA 410 cover after 6 months outdoor exposure in Espoo.

PA 410 samples after outdoor exposure are shown in Figure 69. Major visual changes were not observed, not even in the samples, which were exposed to Greek and Kenyan environments. Although the covers did not contain additional pigments, colour changes did not occur. The susceptibility of PAs to absorb water was observed also after the outdoor exposure. Masses of the PA 410 samples were increased approximately 2 % due to water absorption. The water absorption did not affect the appearance or the rigidity of the cover.

Figure 69. PA 410 samples after 6 months outdoor exposure. Samples from left to right: an unexposed sample and the samples tested in Athens, Oulu, Espoo and Nairobi.

PC/rPET covers maintained their appearance after 6 months exposure in all testing locations. PC/rPET samples after exposures are shown Figure 70.

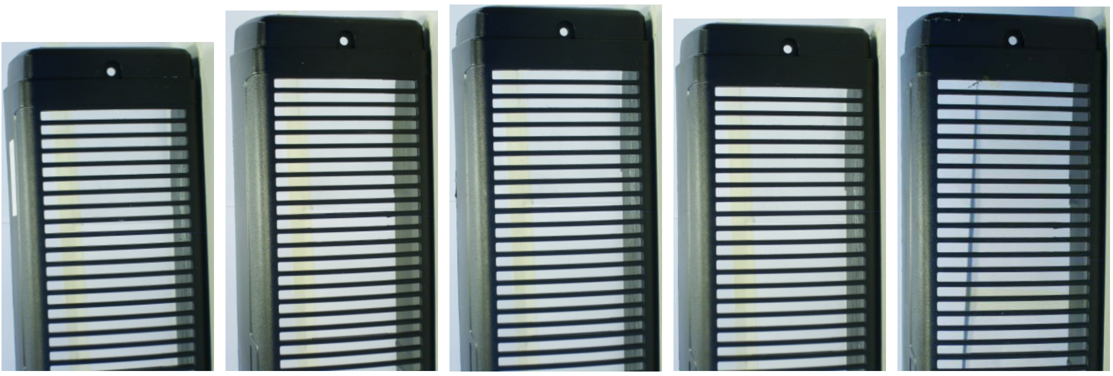

Figure 70. PC/rPET samples after 6 months outdoor exposure. Samples from left to right: an unexposed sample and the samples tested in Athens, Oulu, Espoo and Nairobi.

PTT samples are shown in Figure 71. Some visual changes were observed after the testing. As expected, the colour of the PTT became yellowish during the test. Naturally coloured polyesters generally change colour due to UV radiation. The covers tested in Greece and Kenya became more yellowish than those tested in Finland. UV radiation in Greece and Kenya is much stronger than that in Finland. According to Table 9, UV dose during the test in Athens was over two times higher than that in Finland. Based on the UV indices in Table 9, UV radiation in Kenya was even more severe than that in Greece. Due to high UV-dose rPC 10, rPC 30 and rPC 65 became darker in Greece than those in Oulu or Espoo. Dark coloured rPC 30B, PC/rPET and vPC covers did not change colour notably. Photos of rPC 10, rPC 30, rPC 30B, rPC 65 and vPC are shown in Figure 72, Figure 73, Figure 74, Figure 75 and Figure 76, respectively. Significant visual changes were not observed with the exception of dirt in some corners. The colour change of rPC 10, rPC 30 and rPC 65 is decreased, if darker pigment is used.

Figure 71. PTT samples after 6 months outdoor exposure. Samples from left to right: an unexposed sample and the samples tested in Athens, Oulu, Espoo and Nairobi.

Figure 72. rPC 10 samples after 6 months outdoor exposure. Samples from left to right: an unexposed sample and the samples tested in Athens, Oulu, Espoo and Nairobi.

Figure 73. rPC 30 samples after 6 months outdoor exposure. Samples from left to right: an unexposed sample and the samples tested in Athens, Oulu, Espoo and Nairobi.

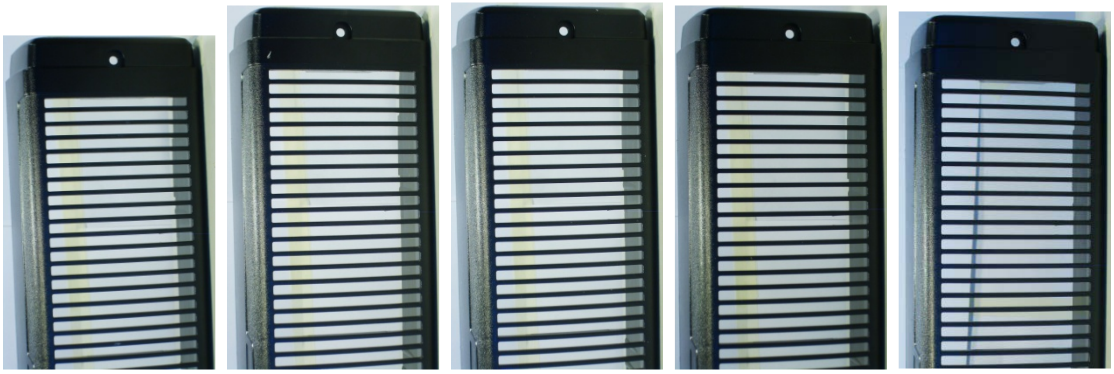

Figure 74. rPC 30B samples after 6 months outdoor exposure. Samples from left to right: an unexposed sample and the samples tested in Athens, Oulu, Espoo and Nairobi.

Figure 75. rPC 65 samples after 6 months outdoor exposure. Samples from left to right: an unexposed sample and the samples tested in Athens, Oulu, Espoo and Nairobi.

Figure 76. vPC samples after 6 months outdoor exposure. Samples from left to right: an unexposed sample and the samples tested in Oulu and Espoo.

14 RESULTS AND ANALYSIS OF LIFE CYCLE ASSESSMENT

14.1 Life cycle impact assessment

The results are presented as midpoint indicators of the impacts categories without normalization and weighting. The primary energy demand and GWP of the production of 1 kg plastics are shown in Figure 77 and Figure 78. GWP with biogenic carbon is considered. In Figure 77 the primary energy demand is divided in non-renewable and renewable energy. In Table 28 the primary energy demand is divided in virgin and recycled material production, glass fibre production and transporting.

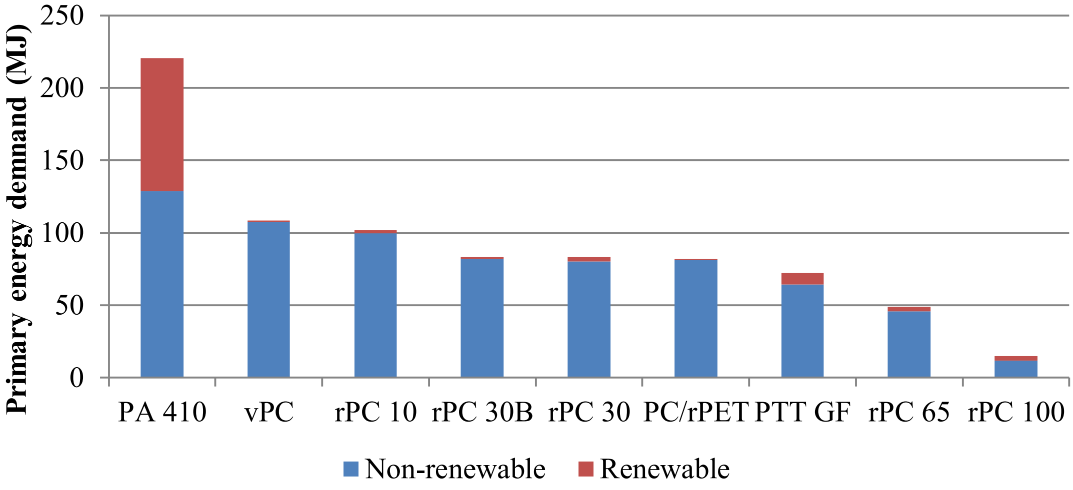

Figure 77. Cradle to Gate primary energy demand of the production of 1 kg plastics.

Table 28. Cradle to Gate primary energy demand of the plastics production. Impacts of transporting of the intermediates of vPC and PA 410 are included in the impacts of virgin material production.

	PA 410	vPC	rPC 10	rPC 30B	rPC 30	PC/rPET	PTT	rPC 65	rPC100
Virgin material	220.59	108.49	92.92	72.27	72.27	72.27	65.23	36.14	-
Recycling	-	-	6.11	9.30	8.48	8.25	-	10.68	13.59
Transport	-	-	2.81	1.69	2.50	1.56	0.24	1.95	1.40
Glass fibre	-	-	-	-	-	-	6.92	-	-
Total	**220.59**	**108.49**	**101.84**	**83.26**	**83.25**	**82.09**	**72.39**	**48.76**	**14.99**

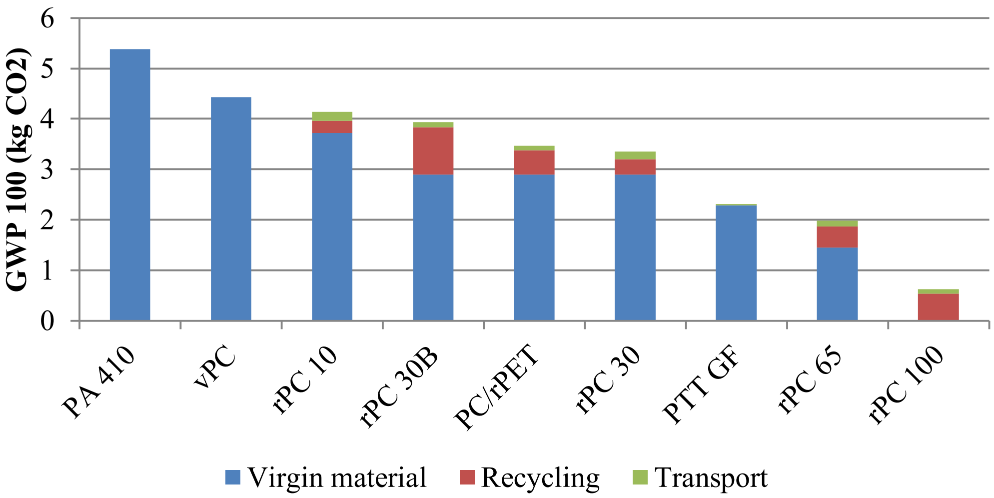

Figure 78. Cradle to Gate GWP100 of the production of 1 kg plastics. Biogenic carbon storage is included. GWP100 is according to IPCC 2013 and GHG protocol.

14.2 Analysis of the results

14.2.1 Recycled plastics

The results show that recycling of PC has a considerable effect on the energy demand and GHG emissions of the plastics production. The GWP and primary energy demand of rPC 100 are only 14 % of those of vPC. The production of virgin PC causes the greatest environmental burden in the rPC and PC/rPET scenarios. For example, the rPC 65 contains 65 % of recycled PC, but the recycling processes causes only 22 % of the environmental impacts. The environmental impacts of rPET are similar as those of the rPC, even though rPET requires a solid-state condensation process. If pre-consumer rPC is used, the environmental impacts are linearly proportional to the recycled material content.

In addition to the amount of recycled material, the used electricity mix, and hence the processing location affects the results. rPC 30B, which is produced in China, requires similar amount of energy as rPC 30, which is produced in Finland. The GWP of rPC 30B is, however, 15 % higher than that of rPC 30. Higher GWP of the rPC 30B production is explained by the electricity mix of China. In China, approximately 76 % of the electricity is produced with hard coal (Itten et al. 2014), which is significantly higher compared to that of Europe. In Europe 25 % of electricity is produced with hard coal. The combustion of hard coal causes high emissions.

14.2.2 Bio-based plastics

Bio-based materials do not necessarily have small environmental impacts. In fact, the GHG emissions and energy demand of PA 410 were highest in this comparison. The impacts of PTT GF were smaller than those of PA 410. High energy demand is particularly due to renewable energy from sun which is required to grow the castor oil plant. Corn field also requires energy from the sun, but the impact is much lower for PTT than for PA 410. The bio-based material content of PTT was lower than that of PA

410, which partly explains the difference in the primary energy demand. The non-renewable energy demand of PA 410 was also high. For example, PA 410 production requires 20 % more energy than vPC production. Another difference in the PA 410 and PTT scenarios was the data source. The environmental impacts of the PA 410 production were directly obtained from the dataset of PE International (2014b), but the model of PTT GF was compiled from various sources. The differences between the PTT GF and PA 410 production could be explained better, if the model of the PA 410 production was self-constructed. However, the data of castor oil farming and processing was not as easily available as the data of corn starch production. In addition, public environmental information of the polymerization of PA 410 was not available. Public data of the PA 410 production may be difficult to find, because PA 410 is a novel material which only has a single producer.

The effect of GF content on the PTT GF is conflicting. The primary energy demand and GWP of glass filled and unfilled PTT are shown in Table 29 and Table 30, respectively. The primary energy demand of unfilled PTT is approximately 4.8 % higher than that of PTT GF. The GWP of unfilled PTT is approximately 6 % lower than that of PTT GF. The results are conflicting due to differences in GF and TPA production. GF production causes relatively larger GHG emissions than TPA production. The ratio of GWP and primary energy demand of GF and TPA production are 0.06 kg CO_2/MJ and 0.04 kg CO_2/MJ, respectively.

Environmental impacts of PTT GF in this study are lower than those according to DuPont (2014c). The GWP and non-renewable energy usage of unfilled PTT calculated by DuPont are 3.38 kg CO_2/kg and 83.8 MJ/kg, respectively. Environmental impacts of unfilled PTT according to this study are approximately 15 - 20 % lower than those of DuPont (2014c). The difference is typical for LCA studies. For example GWP and fossil fuel consumption of unfilled PTT were approximately 2.68 kg CO_2/kg and 56 MJ/kg, respectively, calculated with the data from (Urban & Bakshi 2009) and PlasticsEurope (2014) Most of the uncertainty comes from the modelling of PDO fermentation. Public data of the environmental impacts of PDO fermentation does not exist (Urban & Bakshi 2009). Modelling the PDO fermentation by the fermentation of ethanol may underestimate the impacts.

Table 29. Primary energy demand of the glass filled and unfilled PTT production. Electricity and heat from natural gas are related to polycondensation and compounding processes. Primary energy demand of unfilled PTT is estimated by Urban and Bakshi (2009).

Process	**PTT GF**	**Unfilled PTT**
PDO fermentation	0.16	0.18
Electricity (condensation and compounding)	7.09	7.38
Maize starch	12.05	14.18
Glass fibre	6.92	
Heat, natural gas (condensation and compounding)	0.33	0.33
TPA production	45.61	53.65
Transport	0.24	0.13
Total	**72.39**	**75.86**

Table 30. GWPs of the glass filled and unfilled PTT production. Electricity and heat from natural gas are related to polycondensation and compounding processes. GWP of unfilled PTT is estimated by Urban and Bakshi (2009).

Process	**PTT GF**	**Unfilled PTT**
PDO fermentation	0.01	0.01
Electricity (condensation and compounding)	0.42	0.44
Maize starch production	-0.18	-0.22
Glass fibre production	0.39	0.00
Heat, natural gas (condensation and compounding)	0.02	0.02
TPA production	1.62	1.91
Transport	0.01	0.01
Total	**2.30**	**2.17**

14.2.3 Transportation

Transportation causes relatively small impacts in all scenarios. Transportation has the greatest effect on the impacts of rPC100. 13 % of the GWP and 9 % of the primary energy demand of rPC 100 come from transporting. Transports do not hold large fraction of the impacts of pre-consumer PCs, even though in these scenarios the virgin PC is transported 1 000 km by ship. However, transporting of intermediates in vPC and PA 410 scenarios is not specified, because PlasticsEurope (2014) and PE International (2014b) provided only combined emission and primary energy demand data.

15 DISCUSSION

Based on the previous chapters, a summary of the results is presented in Table 31. The studied plastics are evaluated in three categories: processability, environmental impacts and testing. The properties of the new materials are compared to those of vPC. Each of the categories is explained in details in the forthcoming chapters. Table 31 shows the complexity of materials selection. A single material option is not the optimal choice in every category. Material with low environmental impacts, such as PC/rPET, may not provide sufficient technical properties. Similarly, material moulded at low temperature and pressure may decrease environmental impacts of moulding, but the material's production may cause large impacts during the polymerization. Materials cannot be selected based on one category, but the overall performance counts.

Table 31. A summary of the results and analysis. The properties of the materials are compared in three categories to those of vPC. Environmental impacts refer to the GWP of materials' production.

Material	Processability	Material testing	Environmental impacts
vPC	Reference	Reference	Reference
rPC	Equal	Comparable to vPC if a correct pigment is used.	>25 % lower if more than 30 % recycled material is used
PC/rPET	Requires a different mould, less moulding pressure	Failure in the accelerated aging, loosening of the screws in the temperature cycling.	20 % lower
PTT GF	Requires a different mould, less moulding pressure, asymmetric shrinkage	Changes in appearance without pigments. Some embrittlement in accelerated aging.	50 % lower
PA 410	Requires a different mould, less pressure and temperature.	Changes in appearance without pigments. Water absorption causes notable mass increase.	20 % higher

15.1 Processability of the plastics

Material testing did not bring out clear differences between recycled and virgin PC. However, in moulding some differences were found. The viscosity of the pre-consumer recycled PC was lower than that of virgin PC. It indicates that polymer chains of the PC were degraded during recycling. Because the viscosity of the rPC was decreased, the required injection pressure was lowered. The injection pressure of the rPC 100 front cover was approximately 15 % lower than that of vPC. In rear cover moulding, injection pressure was lowered 25 % for rPC 100. Moulding properties of the rPC 30B were similar as vPC, because rPC 30B contained recycled material from high viscosity PC. The quality of the recycled material must therefore be known, before it is mixed with vPC. To achieve suitable viscosity, high viscosity PC may be required to balance the scission of the polymer chains and the reduction of viscosity. Reduction in viscosity may indicate reduction in mechanical properties.

Moulding of bio-based PTT and PA 410 required less pressure and temperature than moulding of PC. PA 410 required only 1/3 of the injection pressure of PC. PTT and PC/rPET required approximately 2/3 of the injection pressure of the PC. However, the mould designed for PC was not suitable for PA 410 and PTT covers. Dimensions of the PA 410 and PTT covers differed significantly from the vPC covers. For example, the hole distance of the PA 410 rear cover was 2.4 mm shorter than that of vPC. The hole distance of PTT rear cover was 1 mm longer than that of vPC. Shrinkage of the PA 410 was higher than that of PC and shrinkage of the PTT was lower than that of PC. Shrinkage of the PTT in parallel to the flow direction differs from the shrinkage in normal to flow direction. The asymmetric shrinkage of PTT resulted in bending of the covers.

The amount of material in the sample moulding was relatively low for the moulding machine. If more material were moulded, the dimensions and quality of the PA 410 and PTT covers could have been improved. The moulding company did not have previous experience of these materials, which made finding the right parameters more difficult. It was observed that PA 410 and PTT required more careful control of the moulding parameters than PC. Moulding properties of the PC/rPET blend were between those of PC and PTT, which is explained by the similar polymer structure of PTT and PET. Because PC/rPET contains 70 % PC, shrinkage is close to pure PC. Therefore the dimensions of PC/rPET covers were close to those of PC covers. Nevertheless, PA 410, PTT GF and PC/rPET require different mould, if they are used in the high-volume production.

15.2 Materials performance in testing

Material tests and used analysing methods showed that rPC performs similarly as virgin PC. The performance of the rPC in accelerated aging, temperature cycling, water absorption and chemical testing did not differ from that of the virgin PC. The recycled material content as such did not affect the performance of the samples.

Bio-based PTT and PA 410 suffered from visual changes in accelerated aging testing. PTT cover felt more brittle after the test, but the brittleness is not confirmed by measurements. PTT changed its colour during the testing, but the change was minor. PTT contained no colouring additives. Dark coloured PTT cover could survive the test without major degradation, but that must be confirmed with additional tests. PA 410 cover changed its colour significantly from white to orange. The mass of PA 410 cover increased 3 %, but length, width and thickness of the cover were maintained. Surface of the material felt waxy, but degradation of mechanical properties was not observed. The

PA 410 did not contain colouring additives, so colour change is not a major defect. Material should be retested with colouring additives.

PC/rPET covers fractured during accelerated aging. Fractures occurred due to the 30 % PET content. PET is not suitable to be used at 85 °C and 85 % RH for long times. Hydrolysis of PET into alcohol was judged from the IR spectra in Figure 51. The material also became extremely brittle in the test. Different colouring additives did not affect the situation, since both black and green PC/rPET covers failed in the test. PC/rPET covers should be retested at lower temperature, for example, at 65 °C. The requirement to tolerate 85 °C at 85 % RH can be overestimated for a cover part.

Temperature cycling of the covers affected mostly the PC/rPET covers. Covers were attached into aluminium frames with two screws. Tightness of the screws was reduced from 2.5 Nm to below 0.2 Nm during the test. The dimensions of the PC/rPET cover were close to those of PC covers, so the reason for the loosening of the screws is explained by residual stresses from the moulding. PC and PET are different types of polymers. PC is amorphous and PET is partly crystalline. The cover is challenging part for crystalline materials because it contains straight and narrow shapes. Crystallisation of the PET during moulding can induce stresses into cover. These stresses are released and screws loosened during the temperature cycling. Similar releasing of stresses was observed in PTT covers. Opening torque of the screws of PTT cover was only 30 % of the tightening torque. The hole distance of the PTT covers was larger than that of vPC covers, which increased stresses when the cover was attached to aluminium frame. Warpage and bending in the PTT covers further increased stresses.

All materials performed well in the chemical testing. Visual changes were not observed. NaOH traces were seen on the samples, but plastic under the NaOH layer was intact. IR spectra showed some material changes in PC samples, which were exposed to insect spray. Additional peaks may be derived from residual chemical on the material or from new compound which is formed. Tested chemical solutions were mild, which explains the good performance of the material. For example, PAs are susceptible to strong sulphuric acid, but PA 410 did not degrade after 3 % sulphuric acid exposure. Similarly, PTT should degrade in NaOH (DuPont 2014d), but material changes were not observed in this test.

Outdoor exposure of the plastics showed how the plastics tolerate the real operating environments. Material degradation did not occur in Finnish conditions. Relatively mild average temperature and UV-radiation do not damage plastics after 6 months. Thin layer of dirt was the only finding in the samples. Slight colour change occurred in light coloured samples in Greek and Kenyan environments. UV radiation and temperature in Kenya and Greece were higher than those in Finland. Especially high UV radiation caused the colour changes. All the plastics maintained their rigidity and overall performance after 6 months in all testing locations. Small colourings can be controlled by darker pigment. 6 months is not long enough to validate the outdoor usability of the plastic products, whose lifetime is approximately 10 years. Samples were left on the racks at every test site for additional evaluation. As with other tests, mechanical properties of the samples, such as impact strength, should be studied.

15.3 Environmental impacts

According to the GWP and primary energy demand the use of recycled material reduces environmental impacts significantly. Bio-based material can reduce environmental impacts case-specifically. Bio-based material content as such does not guarantee low or high environmental impacts. This study concentrated only in two impact categories and all the impacts of bio-based plastics cannot be evaluated with these impact categories. Differences between recycled and bio-based plastics were observed in the primary energy demand. Bio-based plastics require relatively more renewable energy than petroleum-based recycled plastics. The difference is clearest in the PA 410 scenario: 40 % of the primary energy is derived from sun. On the contrary, only 0.8 % energy demand of the vPC production is derived from renewable sources.

The results of LCA are in line with other studies. Maris et al. (2014) stated that oil extraction and refining requires 95 % of the energy of plastics production. Studies by Arena et al. (2003) and Morris (2005) suggested also that energy usage of plastics recycling is less than 10 % of that of virgin plastics production. The study by Shen et al. (2010) concluded that mechanical recycling of 1 kg PET requires 13 MJ non-renewable primary energy and produces 0.96 kg CO_2. The calculations in this study estimated that primary energy demand of PC production is reduced 86 %, when PC waste is used as raw material instead of crude oil and natural gas. The clear reductions in the environmental impacts are partly explained by the cut-off approach of the recycled material. No impacts are given to the first life of the recycled material. The end-of-life treatment of the studied part was also excluded. However, the cut-off approach points clearly that the greatest impacts of plastics production are derived from extraction and refining of petroleum-based raw materials.

The results of LCA of the bio-based plastics were divided: impacts of PTT were lower than those of vPC, but the impacts of PA 410 were higher than those vPC. Bio-based materials can have higher or lower environmental impacts than petroleum-based materials. Similar observations were also made in other studies. For example, Vercalsteren et al. (2009) found that environmental impacts of bio-based PLA drinking cups are similar as those of cups made of petroleum-based plastics. However, in the study by Shen et al. (2011) the use of partly bio-based PET reduced environmental impacts compared to those of petroleum-based PET. The study by Weiss et al. (2012) showed that bio-based materials cause less GHG emissions but more eutrophication and ozone depletion than petroleum-based materials. The effect of bio-based material content on the environmental impacts is not as straightforward as the effect of recycled material content. The large difference in the results of the bio-based plastics in this study is partly explained by the data sources. The environmental impacts of the PA 410 production were estimated with a complete dataset from PE International (2014b). The PTT GF production was estimated with a data from various sources. The assumptions made by PE International (2014b) may be different than those made in the PTT GF model. These assumptions include the methods how co-products are allocated. Some prefer allocation based on physical or economic value and other prefer systems expansion. The difference between the allocation methods may be larger in case of bio-based materials comparing to those in recycling studies. For example, in the study by Shen et al. (2010) the use of system expansion instead of cut-off approach resulted in 2 times larger energy consumption and 40 % larger GWP.

Recycling of PC and PET causes similar environmental impacts although material properties are different. The differences were clearly shown in the accelerated aging test where the PC/rPET fractured. At high temperatures and RH PET is not as durable material for the cover as PC. According to the current material requirements, PC/rPET cannot be used in the product. Even if the requirements were lightened and the materials could be used without passing the 85/85 accelerated aging testing, the lifetime of PC/rPET cover may be shorter than that of PC cover. The benefits of PET recycling are wasted if more than one PC/rPET cover is needed during the life cycle of a base station. However, LCA results suggest that mechanical recycling of different plastics grades does not differ from environmental point of view. In this study, very similar recycling stages were assumed for both PET and PC. The largest difference between PC and PET recycling scenarios was the solid-state condensation, which was performed only to PET. Eventually the solid-state condensation did not cause significant difference.

In addition, the environmental impacts of the recycling of pre-consumer waste were similar as those of the recycling of post-consumer waste. The additional collection and sorting stages of post-consumer waste do not notably increase GWP and primary energy demand. These environmental impacts do not consider availability of the recycled material, which differs between pre-consumer and post-consumer waste and between PC and PET. Post-consumer waste is available in larger quantities than pre-consumer waste but quality of pre-consumer waste is more probably better than that of post-consumer waste. rPET is available in larger quantities than rPC, but the material properties of rPET are lower than those of rPC.

15.4 Suggestions

After all, results of the material testing and LCA suggest that rPC is suitable material for a plastic cover. Significant reductions of environmental impacts are obtained when PC is recycled. Testing showed that the performance of rPC grades was comparable to that of vPC. Slight colour changes in outdoor environment can be controlled with pigments and flame resistance is obtained with additives. Moulding of rPC is also possible with the same mould as moulding of vPC. If the availability of rPC is sufficient, rPC can substitute vPC.

Bio-based materials in this study provide suitable material properties, but not as large reduction in environmental impacts as recycling. If the recycled material content is over 65 %, environmental impacts are lower than those of bio-based PTT GF. PTT GF contains also 15 % glass fibre, which will make recycling of the plastics cover more difficult. PTT GF cover can be recycled via incineration, but the material cannot be recycled mechanically and remoulded into new products. PA 410 provides even better material properties than PTT GF. In the accelerated aging test, PA 410 covers suffered only from colour changes, but PTT GF also became slightly brittle. High water absorption rate of PA 410 does not cause immediate degradation. Water absorption reduces the stiffness of PA 410, but increases ductility. Bio-based plastics require still more study before they can be applied into products. Properties of the studied bio-based plastics differ clearly from those of PC. For example, behaviour of the PA 410 and PTT GF during moulding is significantly different. However, it must be remembered that bio-based plastics are not a homogeneous group of materials, but their properties depend on the polymer structure just as the properties of petroleum-based plastics. Therefore, bio-based plastics should be studied and classified similarly as petroleum-based plastics. Bio-based plastics require, however, careful treatment in LCA, because including or excluding the renewable energy sources and bio-based carbon in the calculations affects greatly the results.

16 SUGGESTIONS FOR FURTHER STUDY

Materials in this study were moulded into plastic covers which are used for weather protection of base stations. The covers are not mechanically stressed part even though wind and other weather conditions cause varying loads. Because mechanical strength was not regarded as a critical property, material tests were mostly evaluated visually. Same materials could also be used in applications which require sufficient tensile and impact strength. Mechanical tests should be applied, if these materials are further studied or planned to be used in different applications. Testing could include impact testing of the samples exposed to UV radiation, chemicals and high temperatures. Testing of mechanical properties requires usually several standardized test specimens since variations of the yield or impact strength of samples are considerable. Plastic parts, such as covers can be tested by vibration and drop tests, but they cannot be used in traditional tensile or impact tests.

Visual evaluation of the results was challenging, because the sample covers were not coloured as the production model. Colour of recycled PC depended on the recycled material content. Samples became darker, when recycled material content was increased. Bio-based plastics in this study were naturally coloured, so they did not contain additional pigments. Colour of the material may have affected the performance in testing. For example, a plastic with colouring additives did not change colours in accelerated aging testing and outdoor exposure, but naturally coloured plastics did. If further testing is performed, specific colour must be used.

In addition to visual inspection, chemical testing could include mechanical stress. Mechanical stress combined with chemical exposure would tell more about the susceptibility of plastics to ESC. Chemical testing could be performed with additional substances. GR-487 (2013) lists additional chemicals, including kerosene, isopropyl alcohol and ammonia, which were not used in this study. Therefore the chemical testing is not complete according to the standard.

The LCA showed that recycling of PC reduces significantly GHG emissions and primary energy demand. Recycled material content of PC must be at least 30 % so that the environmental benefit would be considerable. The lack of well-organized and reliable PC waste stream prevents the utilisation of recycled PC in large scale production. There are, however, many applications which use PC and consumption of PC is increased constantly (Fukuoka et al. 2010). It suggests that large amount of PC waste is scattered in various waste streams. It should be studied is it possible to organize a recycling programme, which provides enough recycled PC for high volume production of plastic parts. In addition, the economic aspects should be considered. The costs of recycled PC should not be higher than those of virgin PC.

17 CONCLUSIONS

Environmental impacts of a product can be reduced, for example, by reducing materials or selecting materials with low environmental impacts. It was studied in this thesis, if the recycling of plastics and use of bio-based plastics reduce the environmental impacts. Studied materials were virgin PC, pre-consumer recycled PC, post-consumer recycled PC, blend of virgin PC and post-consumer recycled PET, bio-based PA 410 and bio-based glass fibre reinforced PTT. The environmental impacts refer here to GHG emissions and primary energy demand and they were assessed with LCA tool according to SFS-EN ISO 14040 and 14044 (2006) standards.

The results of LCA show that the increase in the recycled material content decreases environmental impacts. Clear reductions were obtained if at least 30 % recycled material is used. Environmental impacts of rPC and rPET do not differ when LCA tool is used. In this case, bio-based materials do not provide clear reductions in the environmental impacts. PA 410 contains 70 % bio-based material, but the environmental impacts were the highest in this comparison. The environmental impacts of the bio-based PTT GF were between those of rPC 65 and rPC 30. The bio-based PTT GF contained 31 % bio-based material. According to the LCA study, the greatest environmental impacts are derived from processing of petroleum-based plastics. This applies both to recycled and bio-based plastics. Some differences were shown between recycled and bio-based plastics. Bio-based plastics require relatively larger amount of renewable energy than recycled plastics. The study showed that the effect of bio-based material content on the environmental impacts is not straightforward. However, bio-based materials provide methods to utilize the versatile properties of plastics and reduce the dependence on crude oil. All bio-based materials cannot be evaluated based on a couple of example materials, because the properties of bio-based materials differ greatly depending on the polymer structure.

Suitability of the plastics to be used in base station was evaluated with material tests. According to these tests, performance of rPC is comparable to that of vPC. Long-term outdoor durability is still to be evaluated, but the results of accelerated aging testing and 6 months outdoor exposure are promising. However, the failures of PC/rPET samples in the accelerated aging test showed that PC cannot be substituted by PET without reductions in material properties. Bio-based PA 410 and PTT GF are useful materials, but they cannot be moulded into the PC moulds. As with recycled PC, the correct colour and flame resistance can be achieved with additives. Bio-based plastics require more studying, because new bio-based plastics with new properties are manufactured. All the properties of the studied bio-based plastics could not be evaluated within one study.

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APPENDIX 1 - LIFE CYCLE INVENTORY TABLES

Table 32. Primary energy demand by energy sources. (PE International 2014a)

	PA 410	PC/rPET	PTT	rPC 10	rPC 30	rPC 30B	rPC 65	rPC 100	vPC
Non-renewable energy	**128.96**	**81.09**	**64.44**	**97.62**	**80.20**	**81.34**	**41.39**	**11.72**	**107.53**
Crude oil	30.12	31.87	21.83	38.78	31.81	30.91	15.82	1.36	42.55
Hard coal	21.73	6.19	8.00	7.37	6.41	12.14	3.54	2.74	8.03
Lignite	8.04	3.03	1.08	3.06	2.54	2.19	1.35	0.63	4.42
Natural gas	59.34	34.64	27.87	41.25	32.69	31.84	16.71	2.15	45.42
Peat	0.03	1.0E-03	6.0E-05	0.39	0.50	-	0.36	0.89	1.5E-03
Sulphur	1.2E-06	2.5E-09	0.02	0.00	7.5E-06	-	1.3E-09	-	1.1E-05
Uranium	9.70	5.36	5.65	6.78	6.25	4.26	3.61	3.95	7.11
Renewable energy	**91.63**	**0.99**	**7.94**	**2.05**	**3.05**	**1.08**	**1.58**	**3.27**	**0.96**
Biomass	0.07	0.06	7.31	1.09	1.41	0.09	1.02	2.50	0.07
Geothermal	0.03	2.0E-03	-	2.6E-03	2.0E-03	2.0E-03	1.0E-03	-	2.9E-03
Hydro power	1.68	0.63	0.48	0.65	0.69	0.75	0.44	0.76	0.44
Primary forest	0.03	9.2E-06	0.09	4.3E-06	0.71	4.7E-06	4.6E-06	6.8E-06	0.03
Renewable fuels	-	8.3E-07	-	2.9E-08	8.3E-07	3.2E-08	4.2E-07	-	1.2E-06
Solar energy	88.12	0.05	1.0E-03	0.06	0.05	0.05	0.02	5.7E-05	0.07
Wave power	1.9E-12	7.6E-07	1.1E-04	9.8E-07	7.6E-07	7.6E-07	3.8E-07	-	0.00
Wind power	1.70	0.25	0.05	0.25	0.20	0.20	0.10	0.01	0.35
Total (MJ)	**220.59**	**82.09**	**72.39**	**99.67**	**83.25**	**82.42**	**42.97**	**14.99**	**108.49**

Table 33. GHG emissions reported according to GHG Protocol (2013). Biogenic carbon content is also presented. GWP100 is calculated multiplying the mass of the GHG by the GWP defined by IPCC (2014).

	PA 410	PC/rPET	PTT	rPC 10	rPC 30	rPC 30B	rPC 65	rPC 100	vPC
Carbon dioxide	8.92	3.22	2.49	3.91	3.22	3.57	2.01	0.79	4.10
Methane	0.02	0.01	0.01	0.01	0.01	0.01	0.01	1.7E-03	0.01
HCFCs	7.0E-09	3.2E-08	3.0E-08	2.6E-08	2.3E-08	1.7E-08	1.8E-08	1.2E-08	2.8E-08
Nitrous dioxide	1.5E-03	8.0E-05	5.3E-04	9.5E-05	8.0E-05	7.5E-05	5.4E-05	2.8E-05	9.7E-05
PFCs	1.0E-08	2.5E-08	1.0E-07	3.0E-08	3.0E-08	2.8E-08	2.9E-08	2.9E-08	6.9E-09
Sulphur hexafluoride	3.7E-08	6.3E-08	1.1E-07	2.7E-08	3.2E-08	1.7E-07	4.2E-08	5.1E-08	3.7E-08
Nitrogentriflouride	3.0E-11	-	-	-	-	-	-	-	-
Total (kg)	**8.94**	**3.23**	**2.50**	**3.92**	**3.23**	**3.58**	**2.01**	**0.80**	**4.11**
Bio-carbon content (kg)	4.57	0.01	0.63	0.10	0.13	0.01	0.18	0.23	0.02

Table 34. All GHG emissions of the production of rPC 10, rPC 30, rPC 65, rPC 100 and vPC. (PE International 2014a)

	rPC 10	rPC 30	rPC 65	rPC 100	vPC
Carbon dioxide	3.91	3.22	2.01	0.79	4.10
Methane	0.01	0.01	0.01	1.70E-03	0.01
Nitrous oxide	9.55E-05	8.04E-05	5.40E-05	2.76E-05	9.75E-05
Bromocarbons, Hydrobromocarbons and Halons					
Halon (1211)	1.76E-09	2.10E-09	2.68E-09	3.26E-09	1.18E-09
Halon (1301)	2.19E-09	1.98E-09	1.62E-09	1.25E-09	1.18E-10
Methyl bromide	1.72E-18	1.66E-18	1.55E-18	1.44E-18	3.11E-19
Chlorocarbons and Hydrochlorocarbons					
1,1,1-Trichloroethane	6.57E-13	8.15E-13	1.09E-12	1.37E-12	1.38E-12
Carbon tetrachloride	1.48E-10	1.54E-10	1.66E-10	1.77E-10	7.56E-11
Chloromethane	1.75E-11	2.17E-11	2.90E-11	3.64E-11	3.69E-11
Dichloromethane	4.94E-06	3.84E-06	1.92E-06	3.84E-11	5.49E-06
Trichloromethane	1.07E-10	1.19E-10	1.41E-10	1.63E-10	1.22E-10
Chlorofluorocarbons					
Trichlorofluoromethane	8.16E-08	6.35E-08	3.17E-08	1.26E-14	9.07E-08
Trichlorotrifluoroethane	2.08E-12	1.87E-12	1.51E-12	1.15E-12	2.47E-14
Dichlorotetrafluoroethane	8.65E-08	6.86E-08	3.74E-08	6.13E-09	9.91E-08
Dichlorodifluoromethane	1.76E-08	1.37E-08	6.83E-09	5.72E-12	1.95E-08
Chlorotrifluoromethane	1.10E-08	8.57E-09	4.29E-09	-	1.22E-08
Hydrochlorofluorocarbons					
Dichlorofluoromethane	1.38E-14	1.25E-14	1.01E-14	7.76E-15	8.37E-15
Chlorodifluoromethane	2.59E-08	2.29E-08	1.76E-08	1.24E-08	2.83E-08
Hydrofluorocarbons					
Tetrafluoroethane	3.85E-07	3.46E-07	2.77E-07	2.07E-07	7.50E-10
Difluoroethane	1.85E-11	1.88E-11	1.94E-11	2.01E-11	6.00E-10
Trifluoromethane	4.40E-12	3.97E-12	3.22E-12	2.47E-12	2.66E-12
Fully Fluorinated Species					
Hexafluoroethane	3.14E-09	3.10E-09	3.01E-09	2.92E-09	6.66E-10
Tetrafluoromethane	2.73E-08	2.69E-08	2.63E-08	2.56E-08	6.20E-09
Sulphur hexafluoride	2.66E-08	3.22E-08	4.18E-08	5.15E-08	4.04E-08
Total (kg)	**3.92**	**3.23**	**2.01**	**0.80**	**4.11**

Table 35. All GHG emissions of the production of PA 410, PC/rPET, PTT GF and rPC 30B. (PE International 2014a)

	PA 410	**PC/rPET**	**PTT**	**rPC 30B**
Carbon dioxide	8.92	3.22	2.49	3.57
Methane	0.02	0.01	0.01	0.01
Nitrous oxide	1.50E-03	7.97E-05	5.25E-04	7.46E-05
Bromocarbons, Hydrobromocarbons and Halons				
Halon (1211)	1.18E-09	4.45E-09	7.95E-09	6.53E-10
Halon (1301)	1.18E-10	1.91E-09	1.98E-09	1.72E-09
Methyl bromide	7.15E-16	1.33E-18	1.53E-14	1.32E-18
Chlorocarbons and Hydrochlorocarbons				
1,1,1-Trichloroethane	1.41E-12	9.49E-13	1.22E-09	5.99E-14
Carbon tetrachloride	7.56E-11	1.62E-10	9.05E-10	2.25E-10
Chloromethane	3.69E-11	2.55E-11	3.74E-08	1.71E-12
Dichloromethane	2.94E-11	3.84E-06	1.82E-08	3.84E-06
Trichloromethane	1.22E-10	1.21E-10	7.80E-09	3.40E-11
Chlorofluorocarbons				
Trichlorofluoromethane	3.34E-14	6.35E-08	1.45E-13	6.35E-08
Trichlorotrifluoroethane	2.47E-14	1.35E-12	1.28E-11	1.33E-12
Dichlorotetrafluoroethane	6.72E-09	6.93E-08	1.14E-08	6.52E-08
Dichlorodifluoromethane	8.71E-12	1.37E-08	4.53E-10	1.37E-08
Chlorotrifluoromethane	2.68E-15	8.57E-09	-	8.57E-09
Hydrochlorofluorocarbons				
Chlorotetrafluoroethane	1.04E-15	-	-	-
Dichlorofluoromethane	8.37E-15	1.40E-14	8.94E-14	8.88E-15
Chlorodifluoromethane	7.01E-09	3.24E-08	2.97E-08	1.72E-08
Hydrofluorocarbons				
Pentafluoroethane	2.81E-10	-	-	-
Tetrafluoroethane	9.26E-10	2.27E-07	4.37E-08	2.45E-07
Trifluoroethane	2.51E-10	-	-	-
Difluoroethane	6.00E-10	3.76E-10	3.39E-10	9.56E-12
Trifluoromethane	1.93E-09	4.44E-12	2.84E-11	2.83E-12
R 245fa	4.99E-09	-	-	-
Difluoromethane	4.21E-11	-	-	-
Fully Fluorinated Species				
Hexafluoroethane	9.70E-10	2.56E-09	1.08E-08	2.82E-09
Tetrafluoromethane	9.12E-09	2.24E-08	8.89E-08	2.48E-08
Sulphur hexafluoride	3.72E-08	6.26E-08	1.09E-07	1.67E-07
Nitrogentriflouride	3.00E-11	-	-	-
Total (kg)	**8.65**	**3.23**	**2.50**	**3.58**

APPENDIX 2 - ELECTRICITY MIXES

Table 36. Energy sources of electricity in different countries as a fraction (%) of the supply mix. (Itten et al. 2014)

Energy source	China	Europe	Finland	Germany	Italy	USA
Hard coal	76.61	25.30	8.95	18.07	11.58	45.62
Lignite	0.00	0.00	0.00	22.31	0.00	1.95
Peat	0.00	0.20	5.47	0.00	0.00	0.00
Industrial gases	0.61	0.00	0.63	1.36	1.48	0.09
Petroleum products	0.66	2.50	0.45	1.33	8.46	1.30
Natural gas	0.88	22.90	11.83	12.59	46.42	20.35
Hydro power	18.57	15.30	18.82	4.24	13.84	6.77
Nuclear	2.06	25.30	23.98	22.18	0.00	19.10
Geothermal	0.00	0.30	0.00	0.00	1.57	0.40
Solar	0.00	0.50	0.00	0.66	0.05	0.06
Wind	0.42	3.90	0.29	6.45	1.44	1.35
Wood	0.07	0.00	10.57	1.29	0.74	0.93
Biogas	0.00	2.50	0.00	1.28	0.08	0.02
Energy from waste	0.00	1.00	0.58	1.63	1.24	0.67
Other	0.00	0.10	0.53	0.00	0.25	0.02
Imports	0.12	-	17.90	6.62	12.86	1.38

APPENDIX 3 - SYSTEM BOUNDARIES OF LCA

Flow charts of LCA study. Charts are made with GaBi 6 software.

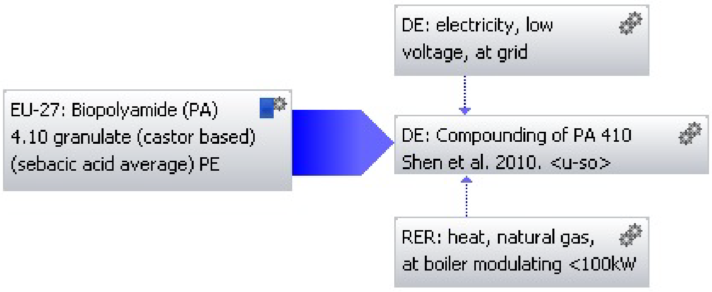


Figure 79. System boundary of the PA 410 production.

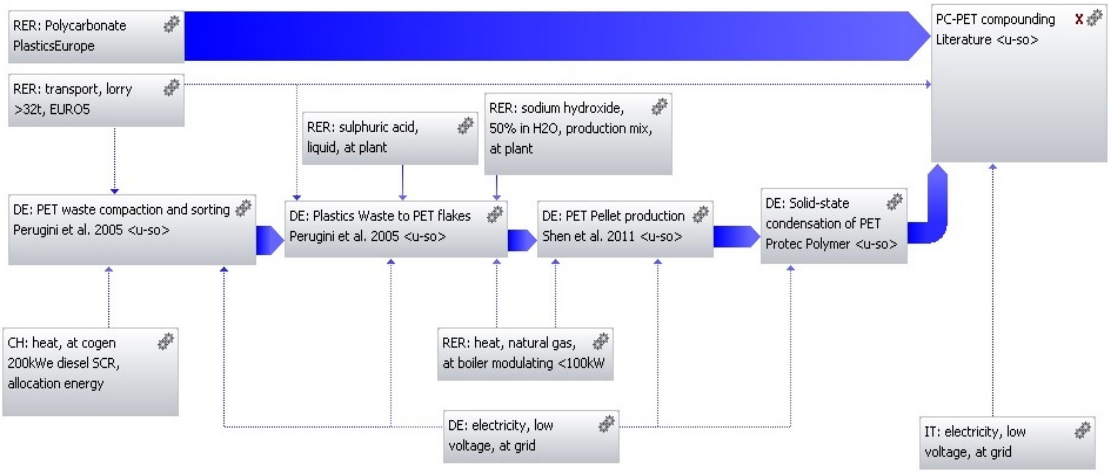


Figure 80. System boundary of the PC/rPET production.

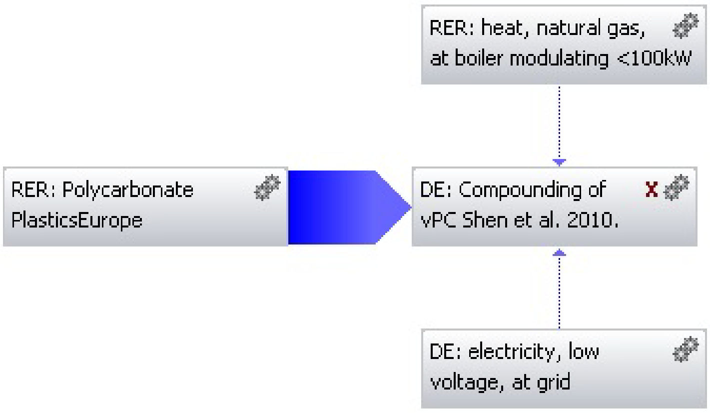


Figure 81. System boundary of the vPC production. (PlasticsEurope 2014)

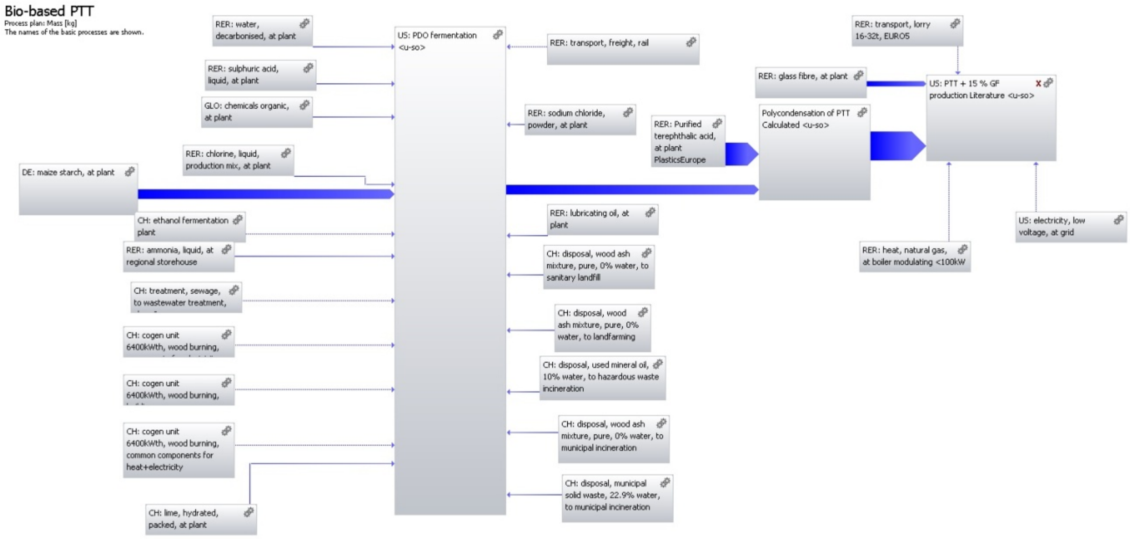


Figure 82. System boundary of the PTT GF production.

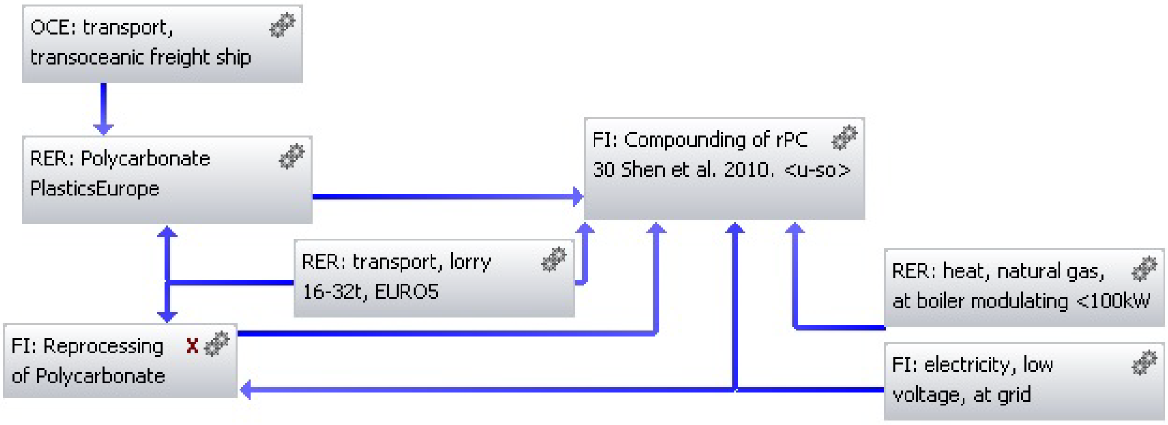


Figure 83. System boundary of the pre-consumer PC production. Same system was used for all pre-consumer PC scenarios.

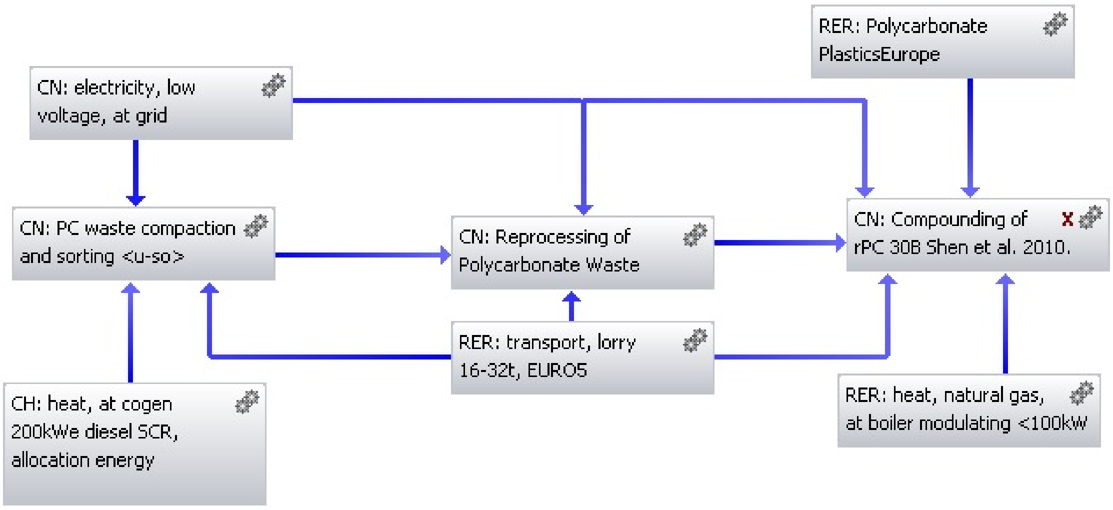


Figure 84. System boundary of the post-consumer PC production.

APPENDIX 4 - DATA OF ACCELERATED AGING TEST

Figure 85. Colour change in PA410 in accelerated aging test. Photos were taken with digital camera after 0 (on left), 500, 1 000, 1 500 and 2 000 h.

Figure 86. Colour change in PC/rPET cover in accelerated aging testing. Photos were taken with digital camera after 0 (on left), 500, 1 000, 1 500 and 2 000 h. Grey material layer was formed on the surface after 1 500 h.

Figure 87. Visual inspection of PTT covers in accelerated aging testing after 0 (on the left), 500, 1000 and 2000 h. Colour of the cover became slightly lighter during the test.

Figure 88. vPC covers in accelerated aging test after 0 (on left), 1000 and 2000 h. The appearance did not degrade during the test.

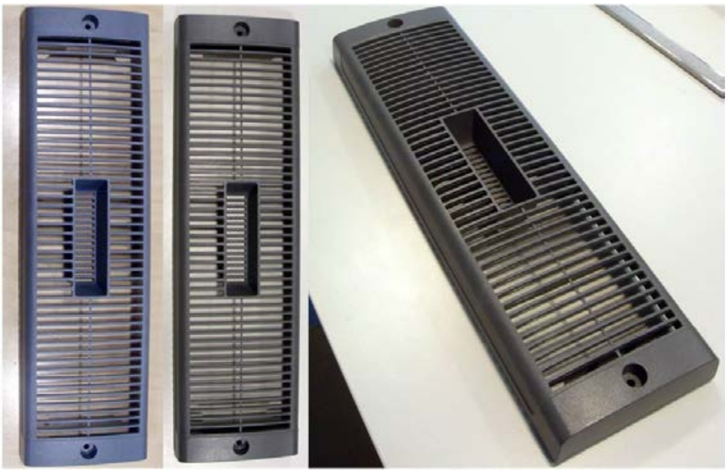


Figure 89. rPC 10 in accelerated aging testing after 0 (on left), 1000 and 2000 h. Changes in the appearance were not observed.

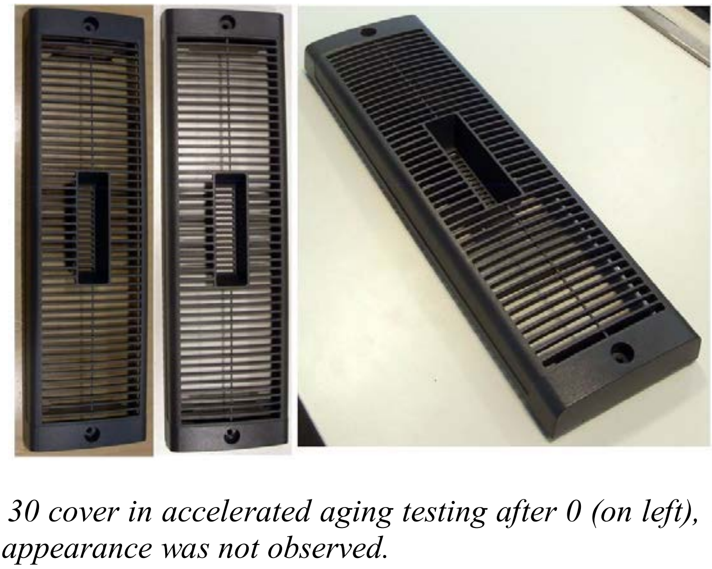


Figure 90. rPC 30 cover in accelerated aging testing after 0 (on left), 1000 and 2000 h. Changes in the appearance was not observed.

Figure 91. No visual changes were observed in rPC 30B cover after 0 (on left), 1000 and 2000 h in accelerated aging testing.

Figure 92. Visual inspection of rPC 65 covers after 0 (on left), 1000 and 2000 h in accelerated aging testing. Material maintained its appearance.

Figure 93. Visual inspection of rPC 100 cover after accelerated aging testing. Pictures are taken after 0 (on left), 1000 and 2000 h.

Table 37. Weighing of the covers before, during and after accelerated aging testing. 2 covers were tested. Only samples #1 were weighed during the test. Scale: Kern CX B.

	Mass (g)					
Sample	**0 h**	**500 h**	**1000 h**	**1500 h**	**2000 h**	**Change**
PA410 #1	245	252	252	247	254	3.7 %
PA410 #2	245	-	-	-	254	3.7 %
PC/rPET #1	279	280	278	267	259	-7.2 %
PC/rPET #2	279	-	-	-	257	-7.9 %
PTT #1	317	319	319	318	320	1 %
PTT #2	317	-	-	-	320	1 %
rPC10 #1	278	279	279	278	279	< 1 %
rPC10 #2	276	-	-	-	277	< 1 %
rPC30B #1	269	269	269	269	270	< 1 %
rPC30B #2	269	-	-	-	269	< 1 %
rPC30 #1	276	277	277	276	278	< 1 %
rPC30 #2	277	-	-	-	278	< 1 %
rPC65 #1	272	273	273	272	273	< 1 %
rPC65 #2	273	-	-	-	274	< 1 %
rPC100 #1	270	271	271	270	271	< 1 %
rPC100 #2	270	-	-	-	270	< 1 %
vPC #1	270	271	271	270	271	< 1 %
vPC #2	267	-	-	-	268	< 1 %

Table 38. Changes in length before, during and after accelerated aging testing. 2 covers were tested. Measurements were performed with slide gauge.

	Length (mm)					
Sample	**0 h**	**500 h**	**1000 h**	**1500 h**	**2000 h**	**Change**
PA410 #1	443.5	443.7	443.7	443.6	444.2	0.2 %
PA410 #2	443.5	-	-	-	443.9	0.1 %
PC/rPET #1	446.2	439.4	439.6	435.2	429.2	-3.8 %
PC/rPET #2	446.2	-	-	-	426.2	-4.5 %
PTT #1	447.3	447.5	447.4	447.2	447.4	0.0 %
PTT #2	447.7	-	-	-	447.6	0.0 %
rPC10 #1	445.4	445.4	445.3	445.3	445.3	0.0 %
rPC10 #2	445.3	-	-	-	445.2	0.0 %
rPC30B #1	445.1	445.1	445.0	444.9	445.0	0.0 %
rPC30B #2	445.3	-	-	-	445.0	-0.1 %
rPC30 #1	445.2	445.3	445.4	445.0	445.2	0.0 %
rPC30 #2	445.4	-	-	-	445.4	0.0 %
rPC65 #1	445.3	445.3	445.3	445.1	445.2	0.0 %
rPC65 #2	445.4	-	-	-	445.3	0.0 %
rPC100 #1	445.5	445.4	445.2	445.1	445.3	0.0 %
rPC100 #2	445.5	-	-	-	445.3	0.0 %
vPC #1	445.2	445.2	445.2	445.0	445.3	0.0 %
vPC #2	444.9	-	-	-	444.9	0.0 %

Table 39. Width of the covers after accelerated aging testing. 2 covers were tested.

	Width (mm)					
Sample	**0 h**	**500 h**	**1000 h**	**1500 h**	**2000 h**	**Change**
PA410 #1	124.80	124.94	124.85	124.26	125.10	0.2 %
PA410 #2	124.69	-	-	-	125.15	0.4 %
PC/rPET #1	125.59	124.33	123.44	121.38	119.51	-4.8 %
PC/rPET #2	125.57	-	-	-	122.97	-2.1 %
PTT #1	125.75	125.74	125.73	125.67	125.70	0.0 %
PTT #2	125.75	-	-	-	125.61	-0.1 %
rPC10 #1	125.33	125.33	125.35	125.33	125.38	0.0 %
rPC10 #2	125.30	-	-	-	125.35	0.0 %
rPC30B #1	125.35	125.32	125.30	125.25	125.31	0.0 %
rPC30B #2	125.30	-	-	-	125.28	-0.1 %
rPC30 #1	125.34	125.34	125.30	125.25	125.31	0.0 %
rPC30 #2	125.35	-	-	-	125.33	0.0 %
rPC65 #1	125.30	125.26	125.25	125.20	125.34	0.0 %
rPC65 #2	125.35	-	-	-	125.25	0.0 %
rPC100 #1	125.36	125.30	125.29	125.25	125.30	0.0 %
rPC100 #2	125.33	-	-	-	125.40	0.1 %
vPC #1	125.33	125.33	125.32	125.25	125.27	0.0 %
vPC #2	125.30	-	-	-	125.29	0.0 %

APPENDIX 5 - MASS CHANGE IN WATER ABSORPTION

Table 40. Mass change of the PA 410, PC/rPET, PTT and rPC 30B plaques in water absorption testing. Specimens were immersed in deionised water at 23 °C.

	Mass (g)			
Time (h)	**PA410**	**PC/rPET**	**PTT**	**rPC30 B**
0	23.3825	25.2146	27.7572	22.6888
24	23.4800	25.2293	27.7745	22.7142
48	23.5144	25.2427	27.7828	22.7285
72	23.5410	25.2500	27.7904	22.7406
170	23.6124	25.2712	27.8080	22.7544
336	23.6924	25.2888	27.8135	22.7599
504	23.7681	25.2983	27.8264	22.7602
840	23.8852	25.3077	27.8478	22.7840
1008	23.9274	25.3106	27.8521	22.7606
1176	23.9561	25.3123	27.8551	22.8234
1344	23.9828	25.3134	27.8580	22.8118
1560	24.0162	25.3128	27.8613	22.7679
1704	24.0372	25.3187	27.8645	22.7515
1848	24.0594	25.3143	27.8676	22.7523
2016	24.0865	25.3153	27.8690	22.7577
2352	24.1283	25.3149	27.8727	22.7520
2568	24.1475	25.3149	27.8727	22.7520
2712	24.1672			
2856	24.1847			
3072	24.2056			
3192	24.2185			
3360	24.2333			
3696	24.2647			

Table 41. Mass change of the rPC 10, rPC 30, rPC 65, rPC 100 and vPC plaques in water absorption testing. Specimens were immersed in deionised water at 23 °C.

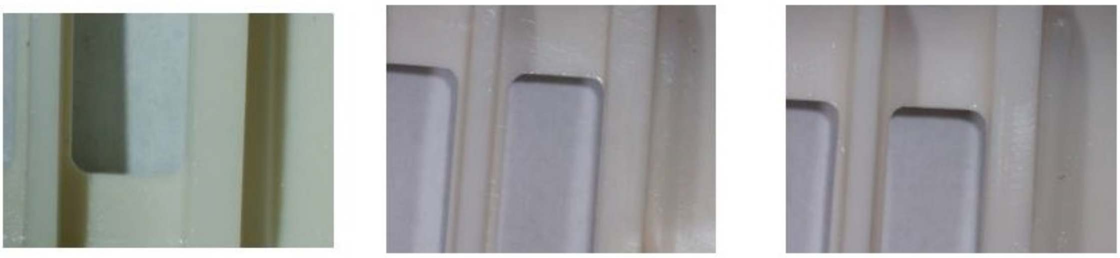
	Mass (g)				
Time (h)	**rPC 10**	**rPC 30**	**rPC 65**	**rPC 100**	**vPC**
0	22.4424	22.5674	22.7570	21.8850	24.3812
24	22.4745	22.6115	22.7891	21.9213	24.4250
48	22.4908	22.6147	22.7994	21.9347	24.4386
72	22.5265	22.6259	22.8247	21.9435	24.4511
170	22.5066	22.6307	22.8203	21.9554	24.4597
336	22.5305	22.6373	22.8741	22.0069	24.4687
504	22.5190	22.6375	22.8332	21.9620	24.4734
840	22.5245	22.6390	22.8440	21.9695	24.4787
1008	22.5213	22.6535	22.8212	21.9632	24.4675
1176	22.5087	22.6441	22.8708	21.9632	24.4942
1344	22.5095	22.6321	22.8264	21.9617	24.4884
1560	22.5156	22.6314	22.8415	21.9628	24.4906
1704	22.5101	22.6308	22.8209	21.9616	24.4662
1848	22.5074	22.6320	22.8209	21.9618	24.4660
2016	22.5094	22.6320	22.8203	21.9613	24.4650
2352	22.5094		22.8199	21.9620	24.4650
2568			22.8199	21.9620	

Table 42. Dimensions (mm) of PC rear covers before and after 72 h immersion in deionized water. Covers were measured with Mitutoyo coordinate measuring device.

Sample	**Condition**	**Hole distance**	**Width: end 1**	**Width: end 2**	**Width: middle**
rPC10	Dry	409.533	127.157	127.162	127.653
rPC10	Wet	409.591	127.589	127.232	128.102
rPC30 B	Dry	409.587	127.021	127.153	127.839
rPC30 B	Wet	409.643	127.204	127.309	127.780
rPC30	Dry	409.539	127.139	127.969	127.331
rPC30	Wet	409.590	127.145	127.139	127.951
rPC65	Dry	409.536	127.108	127.394	128.120
rPC65	Wet	409.598	127.146	127.078	127.714
rPC100	Dry	409.603	127.184	127.268	127.901
rPC100	Wet	409.650	127.116	127.282	127.751
vPC	Dry	409.589	127.158	127.255	127.731
vPC	Wet	409.611	127.126	127.248	127.763

APPENDIX 6 - VISUAL EVALUATION OF CHEMICAL EXPOSURE

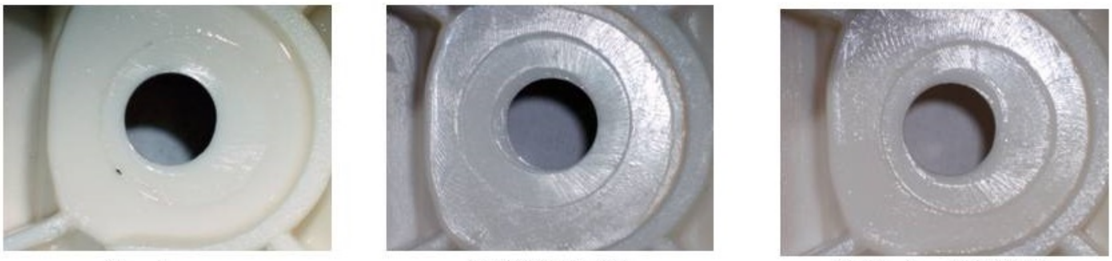
Reference | 0.2N NaOH | Lubricating oil (CRC)



Insect spray | 3% Sulphuric acid | Lubricating oil (WD40)

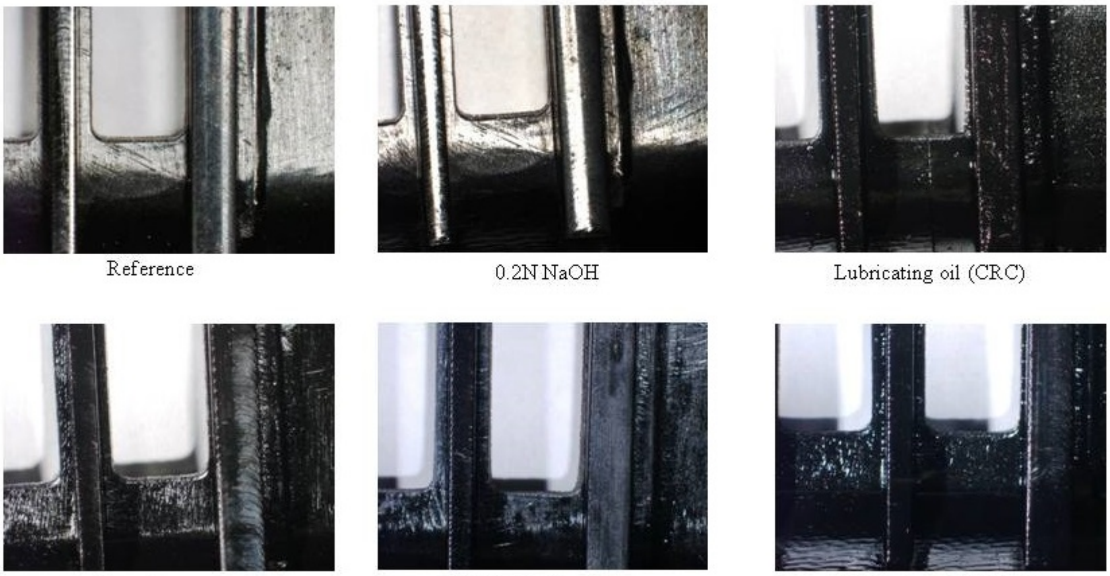
Figure 94. PA 410 after chemical test. Photos were taken with macroscope. Objective magnification was 5.8x. Surfaces of the covers were wiped with water to remove residual chemicals.

Reference | 0.2N NaOH | Lubricating oil (CRC)



Insect spray | 3% Sulphuric acid | Lubricating oil (WD40)

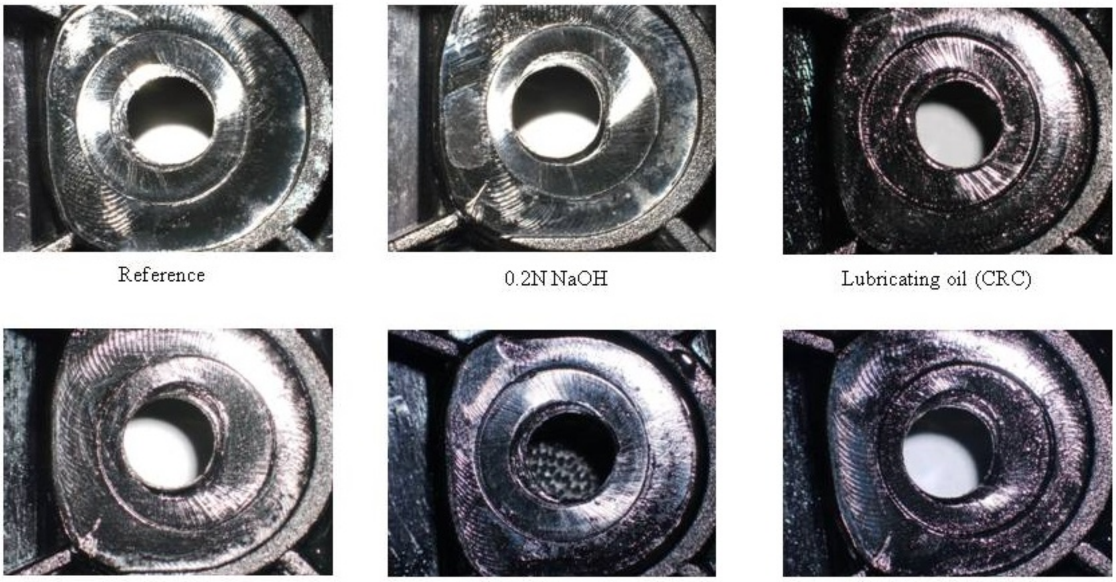
Figure 95. PA 410 after chemical test. Photos were taken with macroscope. Objective magnification was 5.8x. Surfaces of the covers were wiped with water to remove residual chemicals.



Reference 0.2N NaOH Lubricating oil (CRC)

Insect spray 3% Sulphuric acid Lubricating oil (WD40)

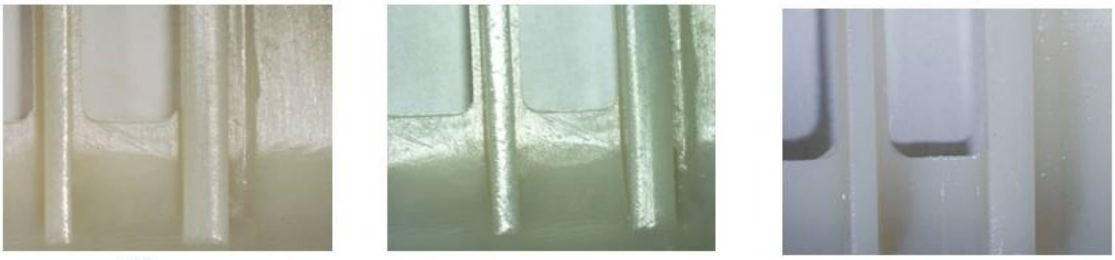
Figure 96. PC/rPET after chemical test. Photos were taken with macroscope. Objective magnification was 5.8x. Surfaces of the covers were wiped with water to remove residual chemicals.



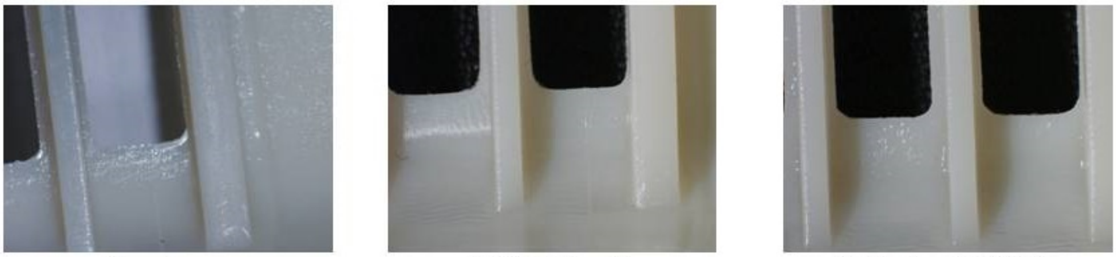
Reference 0.2N NaOH Lubricating oil (CRC)

Insect spray 3% Sulphuric acid Lubricating oil (WD40)

Figure 97. PC/rPET after chemical test. Photos were taken with macroscope. Objective magnification was 5.8x. Surfaces of the covers were wiped with water to remove residual chemicals.



Reference　0.2N NaOH　Lubricating oil (CRC)



Insect spray　3% Sulphuric acid　Lubricating oil (WD40)

Figure 98. PTT after chemical test. Photos were taken with macroscope. Objective magnification was 5.8x. Surfaces of the covers were wiped with water to remove residual chemicals.

Reference　0.2N NaOH　Lubricating oil (CRC)

Insect spray　3% Sulphuric acid　Lubricating oil (WD40)

Figure 99. PTT after chemical test. Photos were taken with macroscope. Objective magnification was 5.8x. Surfaces of the covers were wiped with water to remove residual chemicals.

Reference 0.2N NaOH Lubricating oil (CRC)

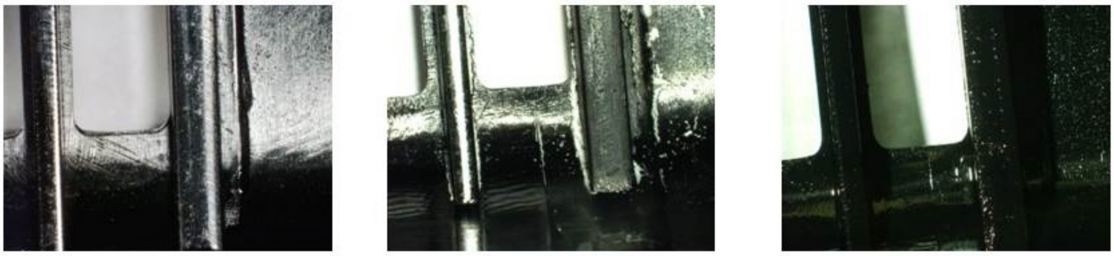
Insect spray 3 % Sulphuric acid Lubricating oil (WD40)

Figure 100. rPC 10 after chemical test. Photos were taken with macroscope. Objective magnification was 5.8x. Surfaces of the covers were wiped with water to remove residual chemicals.

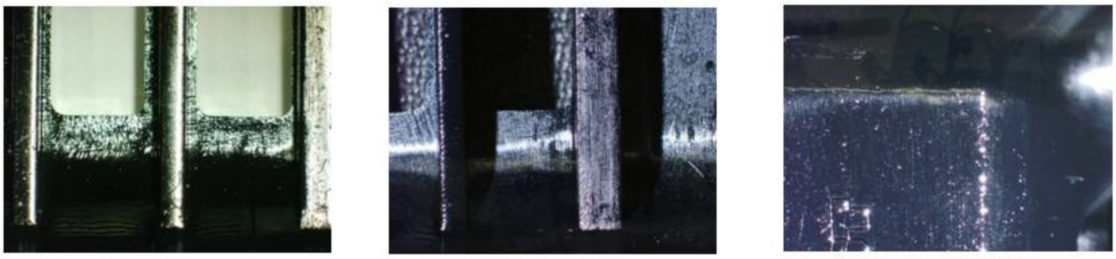
Reference 0.2N NaOH Lubricating oil (CRC)

Insect spray 3 % Sulphuric acid Lubricating oil (WD40)

Figure 101. rPC 10 after chemical test. Photos were taken with macroscope. Objective magnification was 5.8x. Surfaces of the covers were wiped with water to remove residual chemicals.

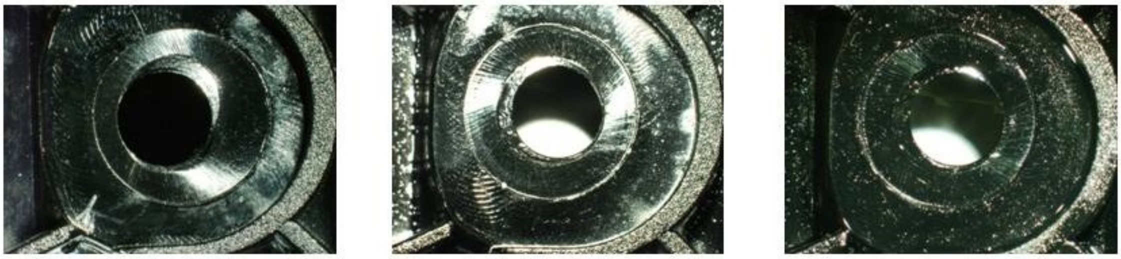


Reference 0.2N NaOH Lubricating oil (CRC)

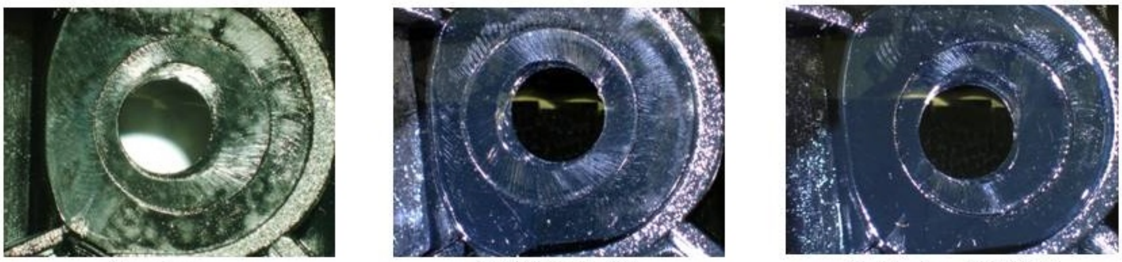


Insect spray 3% Sulphuric acid Lubricating oil (WD40)

Figure 102. rPC 30B after chemical test. Photos were taken with macroscope. Objective magnification was 5.8x. Surfaces of the covers were wiped with water to remove residual chemicals.

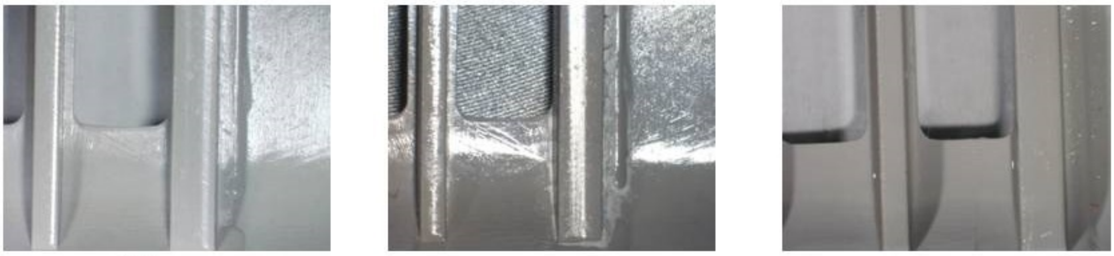


Reference 0.2N NaOH Lubricating oil (CRC)

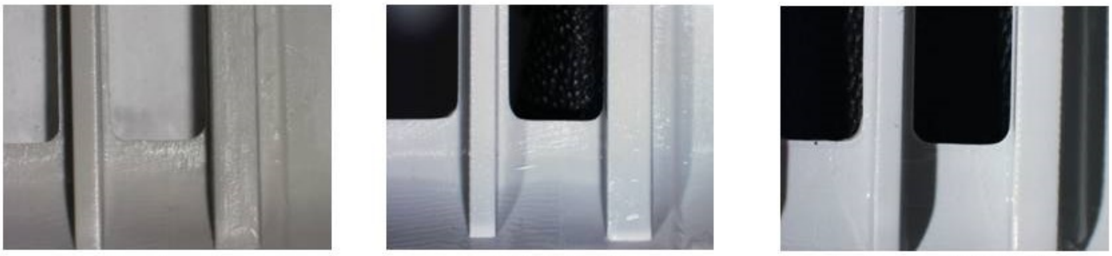


Insect spray 3% Sulphuric acid Lubricating oil (WD40)

Figure 103. rPC 30B after chemical test. Photos were taken with macroscope. Objective magnification was 5.8x. Surfaces of the covers were wiped with water to remove residual chemicals.

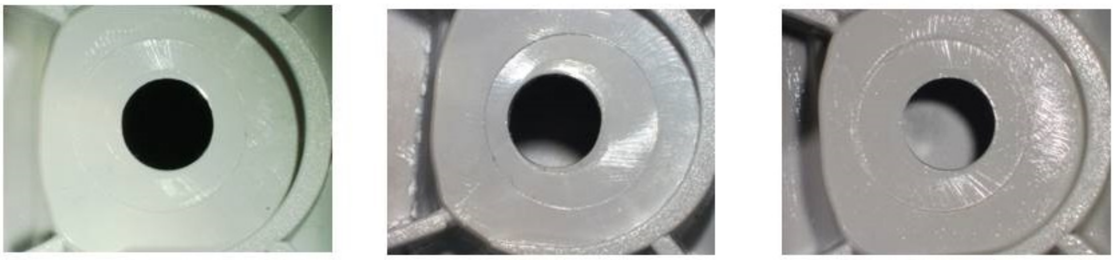


Reference 0.2N NaOH Lubricating oil (CRC)

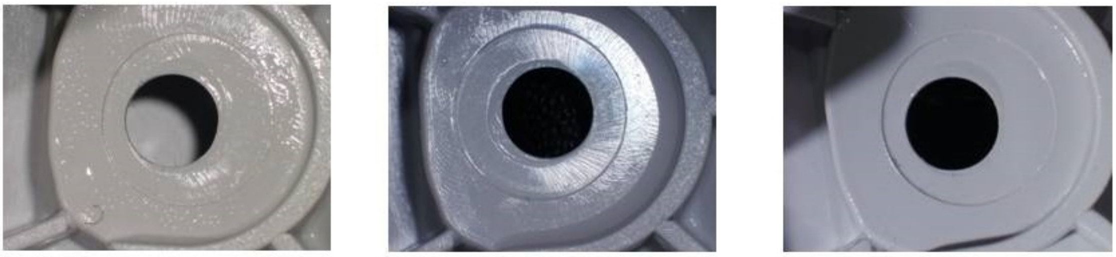


Insect spray 3% Sulphuric acid Lubricating oil (WD40)

Figure 104. rPC 30 after chemical test. Photos were taken with macroscope. Objective magnification was 5.8x. Surfaces of the covers were wiped with water to remove residual chemicals.

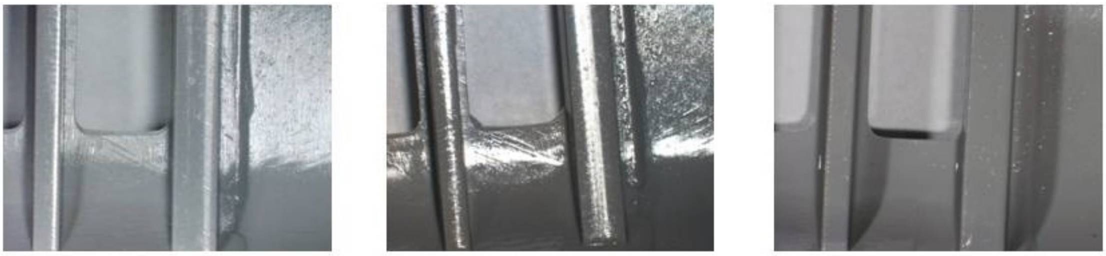


Reference 0.2N NaOH Lubricating oil (CRC)

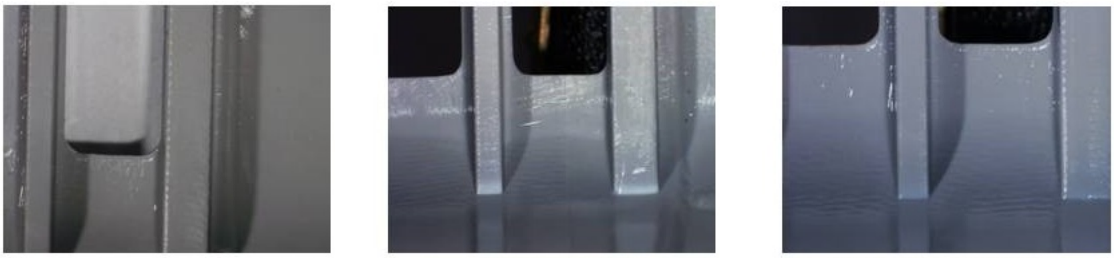


Insect spray 3% Sulphuric acid Lubricating oil (WD40)

Figure 105. rPC 30 after chemical test. Photos were taken with macroscope. Objective magnification was 5.8x. Surfaces of the covers were wiped with water to remove residual chemicals.



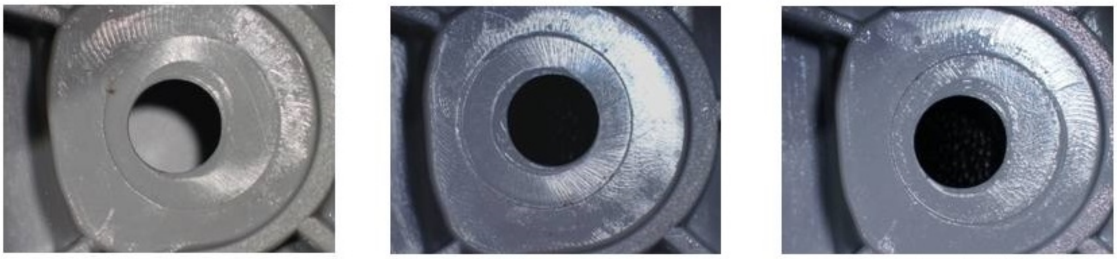
Reference | 0.2N NaOH | Lubricating oil (CRC)



Insect spray | 3% Sulphuric acid | Lubricating oil (WD40)

Figure 106. rPC65 after chemical test. Photos were taken with macroscope. Objective magnification was 5.8x. Surfaces of the covers were wiped with water to remove residual chemicals.

Reference | 0.2N NaOH | Lubricating oil (CRC)



Insect spray | 3% Sulphuric acid | Lubricating oil (WD40)

Figure 107. rPC 65 after chemical test. Photos were taken with macroscope. Objective magnification was 5.8x. Surfaces of the covers were wiped with water to remove residual chemicals.

Reference
0.2N NaOH
Lubricating oil (CRC)

Insect spray
3% Sulphuric acid
Lubricating oil (WD40)

Figure 108. vPC after chemical test. Photos were taken with macroscope. Objective magnification was 5.8x. Surfaces of the covers were wiped with water to remove residual chemicals.

APPENDIX 7 - WEATHER DATA OF OUTDOOR EXPOSURE

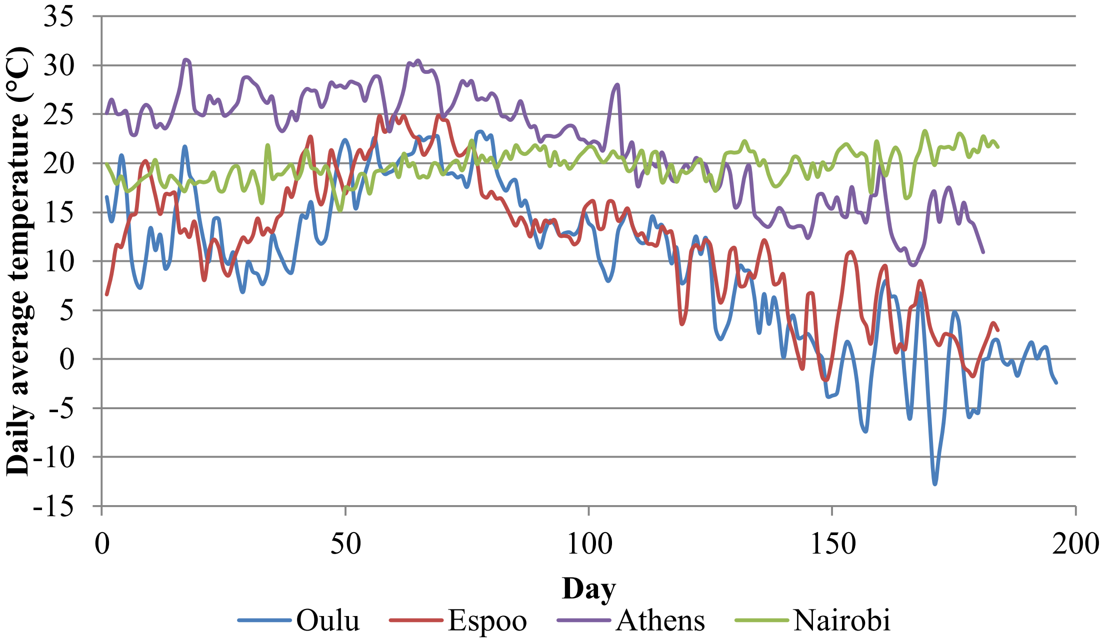


Figure 109. Temperatures at test sites during outdoor exposure. (Relative Prognosis 2014)

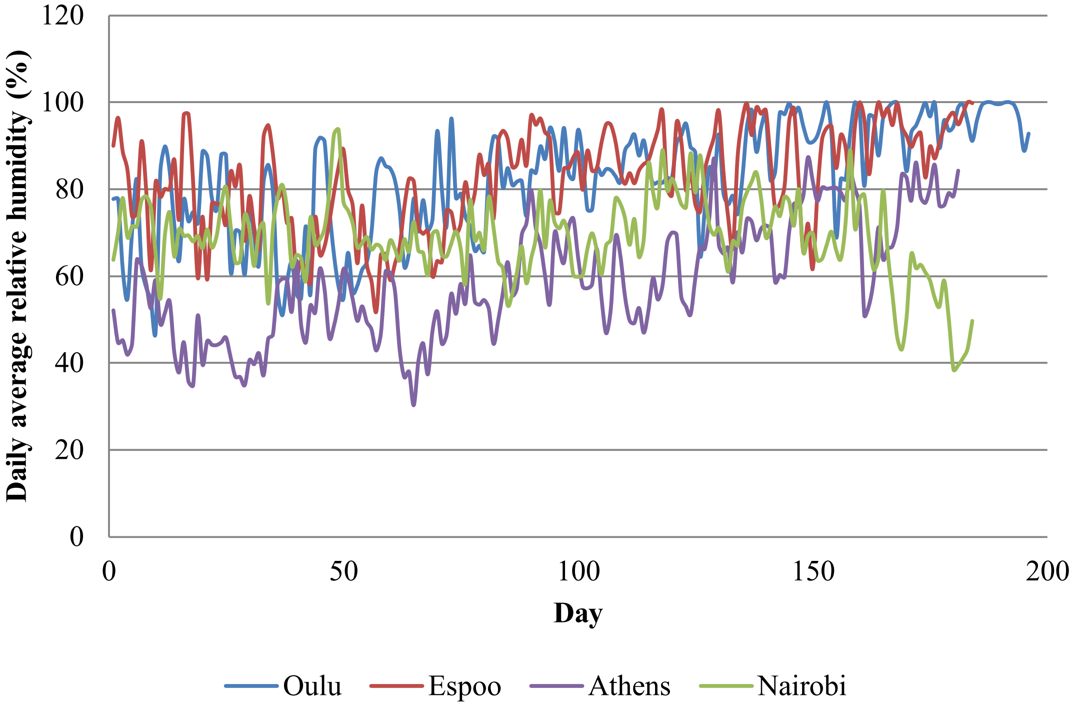


Figure 110. Relative humidity at test sites during outdoor exposure. (Relative Prognosis 2014)

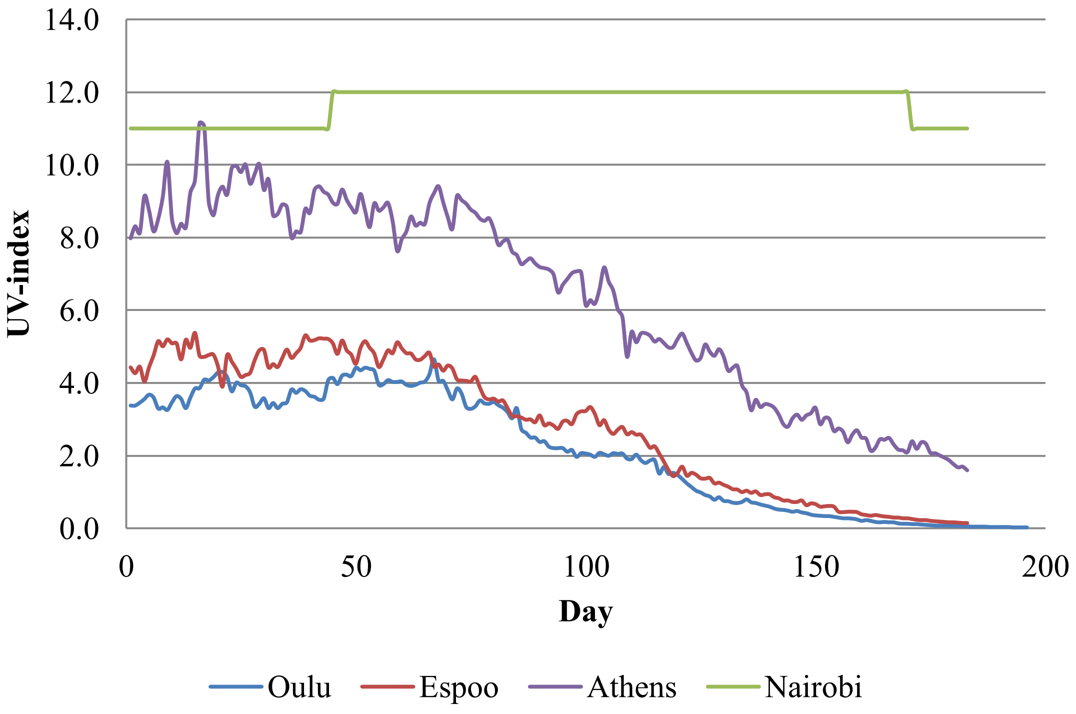


Figure 111. UV-indices during the outdoor exposure. Data of Oulu and Espoo are estimated with measurement data from Sodankylä and Jokioinen, respectively. Data of Athens is measured from the Tatoi Airport. Data of Nairobi is estimated by WHO (2014) . (TEMIS 2014)

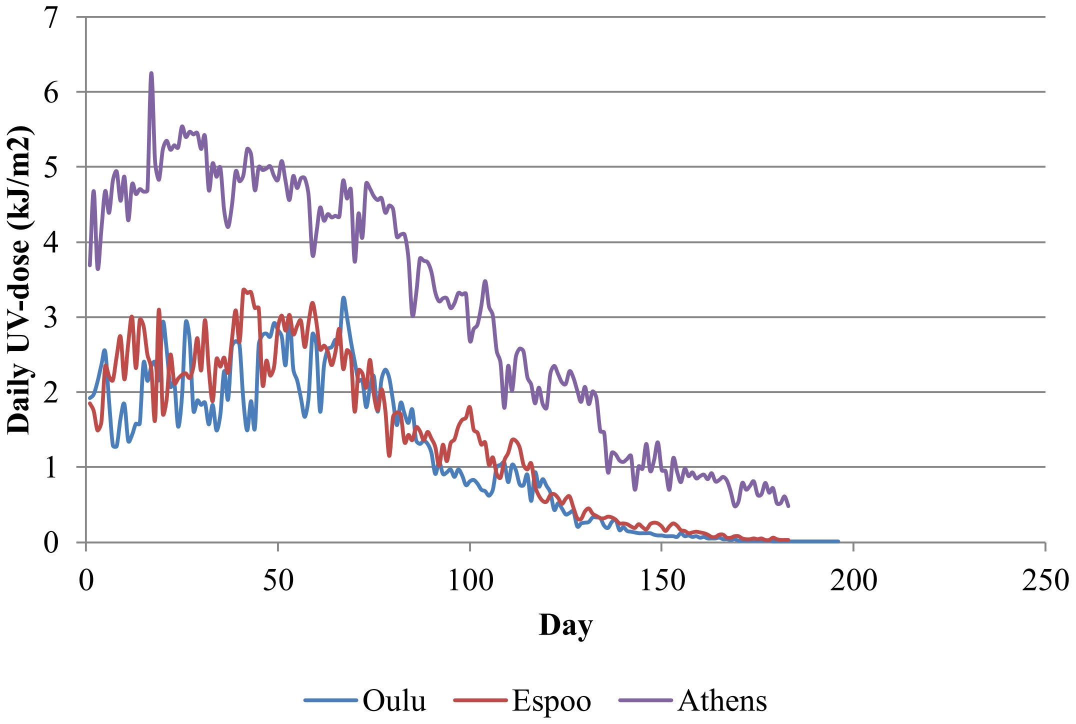


Figure 112. Daily UV-dose during the outdoor exposure. Data of Oulu and Espoo are estimated with measurement data from Sodankylä and Jokioinen, respectively. Data of Athens is measured from the Tatoi Airport. (TEMIS 2014)