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Textile Waste Recovery Potential within the HSY Waste Management Region: Life-Cycle Assessment and Yield Estimation for Textile Waste Collection and Transportation

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The purpose of this thesis was to estimate the annual volumes and collection potential of textile waste within the Capital Region of Finland and to provide a preliminary assessment on the environmental performance of textile waste collection and transportation for Helsinki Region Environmental Services Authority HSY. The study had a connection with circular economy in terms of recovering and providing potent raw material for technical upcycling processes.

The spatial scope of the study was restricted to the waste management region of HSY and the Capital Region of Finland. Regional textile waste accumulation and yield potential were estimated on the basis of indices derived from literature sources and expert advices at HSY. The environmental performance was estimated with a simplified Life Cycle Assessment whose scope was limited to transportation and compensatory related energy consumption and emissions, of which the latter was approached with the impact categories of climate change and acidification. The chosen functional unit was specified as a ton of textile waste and it was applied to three scenarios based on yield estimations in different waste collection configurations. The economic performance of textile waste management was estimated in terms of annual costs and profits for participating properties and the waste management authority HSY. Results and conclusions of the study were affected by the general absence of textile waste-related data and the amount of applied assumptions.

As suggested by the results, a separate collection scheme for textile waste will increase the environmental impact of waste management but to a modest degree. Avoiding production of virgin textile materials may render the climate effect of waste management to neutral, but the overall effect was shunned to negative by replacements in energy production. However, the recovery of textile waste was observed to reduce the annual emissions related to acidification. Prior to any dedicated textile waste collection scheme, a series of pilot initiatives should be launched to gain more robust data on actual textile waste volumes and yields.

Keywords	textile waste, life cycle assessment, waste management

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Tässä työssä selvitettiin pääkaupunkiseudulla vuosittain syntyvän tekstiilijätteen määrää ja keräyspotentiaalia sekä arvioitiin tekstiilijätekeräyksen ympäristövaikutuksia osana Helsingin seudun ympäristöpalvelut (HSY) -kuntayhtymän jätehuollon toimintaa.

Työssä tekstiilijätekeräystä tarkasteltiin HSY:n jätehuoltoalueella Suomen pääkaupunkiseudulla. Tutkimusalueella syntyvän tekstiilijätteen määrää ja saantopotentiaalia arvioitiin edeltäneissä tutkimuksissa esitettyjen indeksien avulla sekä haastattelemalla HSY:n jätehuollon asiantuntijoita. Tekstiilijätehuollon ympäristövaikutuksia arvioitiin yksinkertaistetun elinkaariarvioinnin avulla, jonka laajuus rajattiin kattamaan kuljetusten ja korvaavien tuotejärjestelmien vaikutukset energiankulutuksen ja ilmastonmuutokseen ja ympäristön happamoitumiseen vaikuttavien päästöjen vaikutusluokissa. Tutkimuksen toiminnalliseksi yksiköksi valittiin tekstiilijätetonni ja tätä yksikköä sovellettiin kolmeen eri saantopotentiaalia kuvanneeseen skenaarioon. Tekstiilijätekeräyksen taloudellisia vaikutuksia arvioitiin keräykseen osallistuvien kiinteistöjen ja jätehuollon kustannusten ja liikevaihdon kautta. Tutkimuksen lopputuloksiin ja johtopäätöksiin vaikuttivat tekstiilijätettä käsittelevän tutkimustiedon vähäinen määrä ja tutkimuksessa sovelletut oletukset.

Tekstiilijätteen erilliskeräys lisäisi HSY:n jätehuollon kokonaisympäristökuormitusta mutta vaikutus olisi vaatimaton. Neitseellisen tekstiilituotannon osittaisella korvaamisella olisi mahdollista vähentää ilmastonmuutokseen vaikuttavia päästöjä enemmän kuin niitä syntyy tekstiilijätteen erilliskeräyksessä. Tämä vaikutus voi kuitenkin peruuntua korvaavien polttoaineiden käytöstä energiantuotannossa. Tutkimuksessa havaittiin tekstiilijätekeräyksellä olevan mahdollisuuksia alentaa energiatuotannossa syntyvien happamoittavien päästöjen määrää. Tekstiilijätteen todellisia määriä sekä saanto- ja keräyspotentiaalia pääkaupunkiseudulla tulisi selvittää pilottihankkeiden avulla, joissa tarkasteltaisiin kiinteistöjen halukkuutta osallistua tekstiilijätekeräykseen, toteutuneita keräysmääriä sekä kerätyn tekstiilijätteen laadullisia ominaisuuksia.

Asiasanat	tekstiilijäte, elinkaariarviointi, jätehuolto

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1 Introduction

Textile waste is gaining momentum as a potent raw material for circular economy applications with several initiatives launched to close the loop. The global volumes of annually consumed and disposed textile products have been on a steady increase with an impact on the environment. The lifecycle stages of a given textile product are resource intensive in terms of energy and water consumption, thus suggesting a demand to enhance the material recovery and environmental impact mitigation. Current challenges involve the marginal availability of industrial-scale recycling and sorting technologies as well as a dedicated collection system solely for textile waste.

In Finland the amount of annually generated textile waste accounts for approximately 70000 tons a vast majority of which is recovered as energy. The fraction that is recovered as material is collected and utilized by individual operators with modest contribution to technical recycling. This void in recovery could be enhanced by introducing municipal waste management authorities to organize a separate collection scheme for textile waste. This intervention could serve an ambivalent purpose in terms of increasing the textile quality being collected and the overall yields in textile recovery. Along with these attributes, waste management could provide a local and responsible waste treatment system for materials unsuitable for second hand use or upcycling processes.

Currently, the demand for recycled textile fibres is low due to expectations on the price and quality of the materials but also due to modest production volumes in domestic textile industries. Other challenges for the justification of separate textile waste collection include the additional costs and impacts on the environment. In order to be Pareto optimal, the benefits gained in material recovery should exceed the costs and impacts related to textile waste collection, transportation and utilization. Furthermore, the collection should be based on the purpose of providing material for both reuse and circular economy applications. On this aspect, the future availability of recycling options remains as a keystone that determines the meaningfulness of waste management for textile waste.

1.1 Background and scope of the thesis

This thesis was conducted as an assignment for the Helsinki Region Environmental Authority HSY. The primary tasks were to evaluate the yield potential and annual textile waste accumulation within the Capital Region of Finland and to conduct a simplified life-cycle assessment (LCA) on textile waste collection and transportation. Thus, the spatial scope of this thesis is primarily limited to the HSY waste management region. The research questions applied in this thesis are the following:

- what are the excepted collection yields for textile waste,
- what benefits can be achieved, and
- is textile waste management feasible in Finland?

The first question relates to the effectiveness of textile waste collection in terms of preventing textile waste from being disposed as mixed solid waste. The second question concentrates on the environmental performance of the engaged product systems. In the third question, the barriers and possibilities for a full-scale textile waste recovery scheme in Finland are evaluated.

1.2 EU waste management goals

The European Union waste management principles for the member states are introduced in the Waste Framework Directive 2008/98/EC. These principles are summarized in Article 4 as a five-step waste hierarchy with the primary goal to prevent the formation of waste, to promote measures to increase the recycling and recovery rates and finally to minimize the amount of waste being landfilled. As such, the directive proposes a need to homogenize the waste policies in the member states as well as the need to develop a more unified classification for waste. The primary aim for the latter is to seek ecologically and economically more sound alternatives for waste utilization as is stated in the 22nd introductory wording of the directive. The directive suggests textile waste as such a waste fraction whose classification should be developed further in the member states.

1.3 National legislation on waste in Finland

The Waste Framework Directive has been set to force in Finland as the Decree on Waste (646/2011). The proposals are similar to those in the directive with more weight being given to the prevention of waste related nuisances and more sustainable waste management practices. Responsibilities for municipal waste management authorities are stated in the clause 32 as the responsibility to organize the collection, treatment and reception of municipal waste. In clause 91 the responsibility for the waste management in the Helsinki metropolitan region is betoken to Helsinki Region Environmental Services HSY.

In 2012 the Finnish Council of State decree 179/2012 came into force with an emphasis on increasing recycling rates for waste fractions. By 2015 the recycling rates for selected waste fractions should have increased to 50 % as stated in the clause 14. In the beginning of 2016 the Finnish Council of State decree on landfilling (331/2013) came into force. The decree sets restrictions for waste whose organic carbon concentration exceeds 10 % from being landfilled as stated in the clause 28.

In 2017 a new Finnish nationwide waste management plan for 2023 is published (VALTSU 2017). The current proposal includes goals as stated in the Waste Framework Directive and a strong emphasis on binding municipal waste management into promoting circular economy. As for textile waste, the plan highlights the need to reduce the value added tax for textile repair services in order to enhance the lifetime of current textile products.

Currently there are no legally binding responsibilities regarding waste management for textile waste; nevertheless there are sliver references suggesting a developing momentum, such as the increasing number of textile waste related initiatives both in Finland and the EU.

1.4 Textile waste initiatives in Finland

The Relooping Fashion initiative (Tekstiilien kiertotalous-hanke TEKI) was launched in 2015 as a circular economy pilot for textile waste in association with VTT Technical Research Center of Finland, Helsinki Metropolitan Area Reuse Center Ltd, Seppälä, SUEZ Suomi Ltd, Pure Waste, RePack, TouchPoint, Lindström, Ethica and Tekes. The pilot aims to increase the chemical recycling capacity of cotton by a process developed by VTT Technical Research Center of Finland. In this process the materials are shredded and dissolved into a pulp from which the cotton fibres are recovered into fabrics and further to prototype products.

TEXJÄTE initiative was a research project organized by the Finnish environmental center SYKE. The initiative included projects on textile sorting and recycling technologies, legislative regulation and textile waste accumulation in Finland. The results highlight the importance of preserving the current textile collection networks and the need to develop sorting and recycling technologies. The role of possible extended producer responsibility (EPR) was of importance as an alternative way to arrange the waste management for textile waste through textile product manufacturers, importers and resellers.

Tekstiili 2.0 –initiative was completed in 2016 as a combined effort of Lounais-Suomen Jätehuolto (LSJH), Turku UAS and VTT to study different textile collection schemes, practical sorting methodologies and to develop practical circular economy models for textile waste. The challenges documented involved faulty reporting practices during waste collection, operative errors in the manual sorting and restrictions involved in textile exporting. The initiative is followed by Telaketju -complex with a more extended scope on circular economy approach.

1.5 About HSY

Helsinki Metropolitan Region Environmental Authority HSY is the provider of waste management and water services in the Capital Region of Finland. HSY organises the waste management for public administration and residential properties including the collection, transportation and treatment of the waste. The responsibilities of HSY in terms of waste management are stated in the decree on waste (646/2011) and in the decree on cooperation of municipalities (829/2009). In 2016 the waste management area was compromised of approximately 788000 residential properties in the cities of Helsinki, Espoo, Vantaa and Kauniainen and the municipality of Kirkkonummi as a separate contract area. Along with water services and waste management, HSY provides timely regional data on air quality and the environment.

2 Textile waste: Finland and the Capital Region

2.1 Annual generation of textile waste

There are no official statistics for textile waste accumulation or collection yields in Finland, and as such the estimations presented in this thesis are based on indices proposed in preceding studies (Palm et al. 2014; Dahlbo et al. 2015; HSY 2016; Dahlbo et al. 2017). The annual per capita generation of textile waste in the Capital Region has been estimated to be approximately 10.2 kg (Dahlbo et al. 2015). The per capita amounts of textile waste disposed as mixed solid waste has been observed by HSY in a series of waste composition surveys. According to three sequential surveys, the per capita amount of textile waste disposed as mixed solid waste has remained rather constant at approximately 8.9 kg per capita (HSY 2016). On the basis of these two Capital Region indices, approximately 87 % of textile waste is recovered as energy and 13 % as materials for reuse.

The annually generated textile waste has increased from 70000 tons to approximately 71200 tons during the years between 2010-2012 (Palm et al. 2014; Dahlbo et al. 2017). Factors affecting the trend include the increased consumption of new imported textiles, accelerated variation in fashion and the accumulation of products of fast fashion (Palm et al. 2014). The products of fast fashion are typically inexpensive and low in quality which suggests that the products have a relative short lifetime before disposal. In terms of mass flow, textile waste generated in Finland during 2012 was disposed into mixed solid waste (54700 tons), used textile collection network (16400 tons) and textile storages and sinks (4400 tons) (Dahlbo et al. 2015).

On the basis of the applied indices and the population structure within the Capital Region (HTV 2016), the estimated amount of generated textile waste within the Capital Region in 2017 is shown in Table 1.

Table 1. Population related textile waste accumulation in the Capital Region

Region	Population	Area (km^2)	Population density (pop./km^2)	Textile waste (t)
Helsinki	636576	214	2972	6493
Espoo	274904	312	880	2804
Vantaa	219783	238	922	2242
Kirkkonummi	39174	394	100	400
Kauniainen	9391	6	1603	96
Total	1179828	1164		12034

The proposed estimation in Table 1 is rough in details, but according to the data the Capital Region has the potential to generate approximately 12000 tons of textile waste annually. When applied to the estimated mass flow, approximately 10500 tons are disposed as mixed solid waste and approximately 1510 tons are separately collected and stored.

Sources of textile waste include households, public administration and private organizations. The two latter are excluded from the estimation applied in this thesis due to expected lower volumes in comparison to households. In 2012 it was estimated that selected laundries and textile manufacturers generated approximately 568 tons of textile waste in the Helsinki metropolitan region (Dahlbo et al. 2015). In 2015 it was estimated that the hospitals, schools and day-care centres generated approximately 12 tons of textile waste in the Capital Region (HSY 2016). When combined, these sources generated less than 5 % of the total volume generated in households and thus the exclusion of the sources remain as an acceptable dissonance in the quality of data.

The estimated number of textile products has been derived by reducing the amount of domestic textile production from the sum of textile imports and exports. In Finland the international trade statistics has been provided by the Finnish Custom (Tulli 2017) which has been used to estimate the amounts of textiles being imported and exported. The amount of domestic textile production is estimated from the domestic industrial production statistics provided by Statistics Finland (Tilastokeskus 2016). The product codes are Common Nomenclature (CN) for the Finnish Custom and PRODCOM for Statistics Finland. The selected product codes included all other textile products than those containing leather. Some of the PRODCOM codes were absent of data and it was assumed the production levels were too low for statistics. To provide a normalized value, the average production levels were rounded to the constant of 4000 tons (Figure 1).

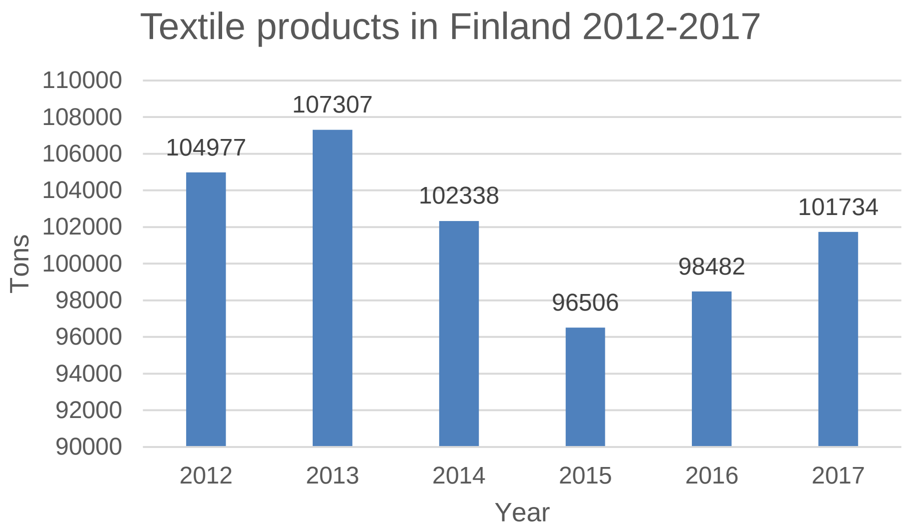

Figure 1. Estimated amounts of textile products in Finland in 2012-2017

The variation in the amount of textile products in Finland has been quite modest. Although the Figure 1 cannot be applied to the Capital Region directly, the data and the waste composition surveys suggest that the amounts of generated textile waste and textile products share some correlation in terms of volume.

Parallel to waste management and used textile collection, textile waste is stored and traded in individual networks. The amounts of textiles being stored permanently or temporally are unknown (Dahlbo et al. 2015) as well as the amounts of textile being illegally collected or stolen from official networks (Watson et al. 2016). Person-to-person trading of textile products has been increased along with the availability of internet-based market places. Table 2 shows the amount of available used textile products in five different Finnish web stores during May 2017.

Table 2. Amounts of available used textiles in selected web stores in May 2017

	Web store				
Textile (pcs.)	**Tori.fi**	**Huuto.net**	**Vähänkäytetty.fi**	**Emmy.fi**	**Rekki.fi**
Clothes	49173	55053	16595	14934	3790
Garments	6439	2629	1846	890	263
Childrens clothes	27690	18346	12301	11800	780
Home textiles	9484	9742	767	0	0
Total	**92786**	**85770**	**31509**	**27624**	**4833**

The mass volumes of the circulated textiles cannot be determined from the number of products, but the data suggests that there are operative parallel systems with considerable turnover and modest amount of statistical data.

2.2 Material properties of textile waste

The material composition of textile waste is assumed to follow the composition of consumed new products. In the study by Schmidt et al. (2016) it was estimated that the average fibre composition of textile waste generated in the Nordic Countries is composed of cotton (57 %), polyester (34 %), wool (4 %) and other natural and synthetic fibres (5 %). In the context of Capital Region the textile waste contains approximately 6900 tons of cotton, 4100 tons of polyester, 500 tons of wool and 600 tons of other fibres.

The material density of textile waste is used to estimate the volumes occupied by a given mass of the waste. As proposed by EPA (2016) the density of loose and unsorted textile waste is approximately 89 kg/m^3 and the density of baled and compressed textile materials approximately 400 kg/m^3. Of the two estimations, the first is applied to this thesis. The volume of the waste can be determined by dividing the mass of the waste with its density which provides a basis to evaluate the storage capacity required in waste management.

The chemical composition of new and second hand textiles has been identified in a study conducted by the Swedish chemical agency (KEMI 2014). The study revealed that the sampled textiles contained approximately 3500 different chemical compounds of which only 1500 compound were registered in the REACH database of the EU chemical agency. Approximately 10 % of the identified compounds were either directly or indirectly harmful for the environment which included acid and azo based colour pigments and odorants. In the study, the chemicals were categorized related to purpose (flame retardants, water-repellent, colour pigments), process (organic solvents, acids, basics) and unintentional (raw material impurities, heavy metals, PAH- and POP-compounds) compounds.

In energy recovery, textile waste is incinerated simultaneously with other waste fractions disposed as mixed solid waste. The lower heating value (LHV) of textile waste refers to the amount of energy that can be recovered in optimal conditions (Conesa et al. 2009). Based on the estimations by Schmidt et al. (2016), a given ton of Nordic textile waste has the average LHV of 20.7 GJ (Table 3).

Table 3. Lower heating values (LHV) for textile fibres according to Schmidt et al. 2016

Fibre	Proportion (%)	LHV (MJ/kg)	Ton of textile waste (MJ)
Cotton	57	20.2	11514
Polyester	34	21.2	7208
Wool	4	23.2	928
Other	5	20.2	1010
Total			20660

The energy content varies according to textile material composition but the variation is modest in magnitude. In their study, Conesa et al. (2009) estimated that a ton of generic textile material releases approximately 20.6 GJ of energy when incinerated which is almost the same as in the estimation derived from Schmidt et al. (2016).

2.3 Separate textile collection in Finland

The present textile collection network is composed of both non-profit and commercial operators with similarities in the collection network structures. Used textiles are being collected in specific curb-side containers (i.e. textile banks), stores and in stationary recycling points. Competition for good quality second hand products has increased among the operators as the number of operators has increased and the general quality of the donated textiles has decreased (Watson et al. 2014; Dahlbo et al. 2015). In 2017 the Capital Region contained approximately 312 registered textile banks, 86 second hand shops and 102 recycling points each accepting used textile donations from consumers.

Three of the largest non-profit operators in Finland are U-landshjälp från Folk till Folk i Finland rf (UFF), Fida International Association (Fida) and the Finnish Red Cross (SPR), whose combined nationwide yield was approximately 14870 tons in 2012 (Dahlbo et al. 2015). Furthermore, several brand stores and shops have begun to accept used textile donations and in 2017 the number of shops accounted for approximately 54 within the Capital Region (Figure 2).

Figure 2. Number of shops accepting used consumer textiles in the Capital Region

Used textiles are being collected in cooperation either with other second hand operators or sorting and recycling centres in Finland or abroad. For example, prior to her bankruptcy Seppälä collected textile waste for Relooping Fashion initiative and textiles suitable for reuse for Recci. Other brands, such as KappAhl, Hennes & Mauritz and Lindex, deliver donated textiles into sorting centres abroad whereas Finlayson utilizes the collected textiles in its own manufacturing processes.

The collection network in Finland is similar to those in Europe. In Europe the door-to-door and kerbside collecting are more frequent. Of the Nordic Countries, Denmark has the strictest regulation since the collection permits are granted solely by selected municipal authorities and the admittances are typically in favour of non-profit organizations (Palm et al. 2014). Although the collection is typically concentrated on recovering used textiles textile in some countries textile waste is separately collected to some extent. In the Netherlands, for example, there are some occasions in which textile waste has been collected in cooperation between non-profit organizations and commercial waste collection operators (WRAP 2015).

2.4 Waste management in HSY

HSY is the responsible authority for waste management in the Capital Region and waste collection and transportations are subcontracted to private waste operators. These operators are responsible for providing the transportation equipment for the waste collection and are free to organize the collection routes within their contracted areas. The contracts between HSY and the waste operators are reviewed frequently based on criterions on the timeliness of the operator’s equipment and the recorded quality of service.

The collection systems available at HSY waste management include property-specific collection, recycling point collection, Sortti station collection and touring vehicle collection. In the two first systems, the waste is collected from the proximity of the origin of the waste, whereas in the two latter systems the consumers are more responsible for transporting the waste into the designated collection points.

In 2016 the property-specific collection points included approximately 77760 properties in the Capital Region with the total yield of approximately 260800 of municipal waste (HSY 2017b). In 2017 there were approximately 137 recycling points in the Capital Region which are managed by Rinki Ltd in cooperation with HSY. The recycling points have several containers for separately collected waste fractions, namely glass, cardboard, metals, plastics and in some units also for used textiles that are collected in cooperation with both non-profit and for-profit organizations. In 2017 there were five Sortti stations in Helsinki (Kivikko and Konala), Espoo (Ämmässuo), Vantaa (Ruskeasanta) and Kirkkonummi (Munkinmäki). The stations accepts the waste directly from the consumers which is then delivered to further treatment and disposal in appropriate waste treatment facilities in the Capital Region. Albeit access to the stations is rather limited, in 2016 the stations received approximately 403000 customer visits in total (HSY

2016). The touring vehicle collection is arranged twice a year by HSY and Helsinki Metropolitan Area Reuse Centre Ltd for the separate collection of e-waste, scrap metal and hazardous waste from households. In 2016 the HSY collection included approximately 300 locations with the total yield of approximately 380 tons (HSY 2016).

2.5 Yield estimation for textile waste collection

Yield is used to refer to the intended output of a given process, and in the context of this thesis yield is used to describe the turnover of textile waste in different collection setups. Similarly, yield can be used to assess the effectiveness of the selected collection systems in terms of waste recovery. Factors affecting the waste collection yield are the amount of waste being generated, ease of access to the collection points and the willingness of the consumers to deliver waste into designated collection pathways (Kautto et al. 2009; Ekström & Salomonson 2014). On the basis of these factors, yields can be expected to be greater in collection systems with close proximity to the source of waste.

In this thesis the yields are estimated based on property-specific collection and recycling point collection. These systems are generally easy to access and more convenient in delivering textile waste than those of Sortti stations and touring vehicle collection since the two first systems requires less use for passenger cars and costs of transportation. There are no statistics for textile collection yields in Finland and thus the proposed estimations are based on a study by Leiviskä (2015) where the effect of two parallel collection systems on the yield of glass waste was observed.

In 2014 approximately 77090 tons of glass waste was generated in Finland and the waste was collected only at recycling points (Rinki 2016). The initial yield at the recycling points was 2150 tons in total which reduced to 1104 tons with the initiation of separate glass waste collection at the properties during 2014. The introduction of property-specific collection reduced the yield at the recycling points by 51 % but increased the total yield of glass waste by 1011 tons. This seems to suggest that the collection system with easier access receives a larger turnover, but does not completely shun the parallel alternative. A rough estimation about the total yield in glass waste is 19 % which is applied to the case with textile waste.

On the basis of the estimated textile waste volumes in the Capital Region, the 19 % yield potential accounts for approximately 2000 tons i.e. the amount that can be prevented from being disposed as mixed solid waste. In proportion to the glass waste example, the expected initial yield at the recycling points is approximately 1360 tons with the gradual decrease to approximately 660 tons with the introduction of property-specific collection. As such the expected combined yield for textile waste may vary between 1960 and 2000 tons at the first year of collection. The yield estimations are calculated based on inhabitant data presented in Table 4.

Table 4. Inhabitants per different property sizes in the Capital Region in 2014 (HSY 2016)

Properties	Inhabitants (2014)
1 apartment	104135
2-4 apartments	91453
5-9 apartments	48390
10-19 apartments	72884
≥ 20 apartments	740991
Total	1057853

On the basis of the data in Table 4, the estimated yields in different waste collection configurations are calculated and presented in Table 5.

Table 5. Estimated textile waste yields in different waste collection configurations

	Estimated annual yields (t)	
Collection configuration	Property-specific	Recycling points
Recycling points only, no properties	0	1360
Voluntary for all properties, no recycling points	308	0
Mandatory for ≥ 20 apartment properties + recycling points	1436	564
Mandatory for ≥ 20 apartment properties, voluntary for other properties, no recycling points	1528	0

The mandatory collection refers to a situation in which the waste management regulations oblige the selected property types to provide waste containers for textile waste. In voluntary collection, the properties can choose to participate in the collection with related obligations of providing the waste containers. In the second configuration, at most 15 % of the properties are voluntarily joined in the collection assuming the availability of collection points increases the yield. However, the actual participation rate is likely to be below this estimation. In the third configuration, the yield in property-specific collection is derived by multiplying the number of inhabitants with the textile waste generation index and the estimated turnover of 19 %. In the fourth configuration, the value is added with the estimated yield from properties other than 20 or more apartments and with the participation level at 15 %.

These are rough estimations that are based on previous research observations. The actual yields for the first year of collection may remain below the estimated volumes but also gradually increase to more efficient levels as the waste management progresses. To gain more insights on the yield, a series of pilot runs should be conducted to measure the actual turnover and to identify relevant parameters affecting the yield. This is shortly discussed in the conclusions of this thesis.

3 Life-cycle assessment for textile waste

Life-cycle assessment (LCA) is a tool to assess the environmental performance of a product, process or a service from design stage to disposal and waste management (Koskela et al. 2010, p. 16). A common basis for LCA studies is founded in a series of ISO 14040 standards that offer guidelines to enhance the comparability of individual LCA studies. The standards suggest a structural composition according to which the studies should be formulated into scope and goal definition, inventory analysis, impact assessment and interpretation of the results. The scope and goal definition sets the limits to the amount of details and to the system being studied as well as temporal dimension of the study. In the inventory analysis the applied data, methods and formulas for calculations are presented. In impact assessment the data provided in inventory analysis is applied to assess the environmental impacts in given impact categories which are typically related to impacts on human health, ecological environment and natural resources. During interpretation the consistency of the results is assessed based on the applied data, assumptions, methods and system restrictions.

LCAs are typically applied into manufacturing processes but the methodology can be applied also into waste management (Cherubini et al. 2009; Iriarte et al. 2009; Rives et al. 2010; Assamoi & Lawryshyn 2012). In waste management studies the functional unit is typically determined as the amount of selected waste generated within an area within a given time period. Examples of this include the amount of municipal waste produced in 12 months in a city district with high population density (Cherubini et al. 2009) and the required waste management capacity for processing the annual production of waste in a city (Assamoi & Lawryshyn 2012).

In the context of textile materials, the system limit is usually limited to the manufacturing and processing of the raw materials (Woolridge et al. 2006; Ekström & Salomonson 2014). Kozlowski et al. (2012) has been criticizing textile material LCA studies for their inconsistency and general incomparability. The studies are often limited to the best known materials, such as cotton and polyester, and the other materials are often ignored. The studies on the cotton and polyester differ in terms of applied methodologies and the observed results contain high levels of variability.

3.1 Scope and goal definition

The goal of this LCA study is to provide a simplified view of the environmental impacts resulting from textile waste collection and transportation as a part of HSY waste management. The environmental impact of waste transportation is observed in the impact categories of climate change and acidification. These categories were chosen as representatives due to the ample amount of available data and the linear relationship between the emission levels and their effect on the ecosystems. The effects of compensation are observed as replaced processes in virgin raw material manufacturing and energy production. These two compensatory systems were selected to represent the possible benefits and adverse effects in terms of robust circular economy design. Due to the simplified structure of the study, the goal is not to provide an exhaustive environmental account but to provide a foundation for a more detailed work in the future.

3.2 Functional unit and applied assumptions

Functional unit is a normalized factor that can be used as a common unit in measuring the environmental performance of a given product system, process or service (Koskela et al. 2010). In this study the selected functional unit is a ton of generic textile waste generated within the Capital Region. Due to lack of data on waste accumulation and generation rates the time period is excluded and the study is conducted as a derivate based solely on the mass of the waste.

The following assumptions are applied during the study:

- separate collection reduces the proportion of textile waste in mixed solid waste,
- textile waste is uniformly distributed spatially in the Capital Region,
- the accessibility of a given collection system affects its yield,
- parallel collection systems affect each other’s yields,
- collected textile waste is transported to Ämmässuo waste treatment centre.

The system boundary begins at the waste formation i.e. when the waste is being disposed and contains the product systems for textile waste, collection and transportation. The products systems that are excluded are the manufacturing and cargo transportations for the collection vehicles and consumed fuel and material recovery of textile waste. The system boundary is summarized in Figure 3.

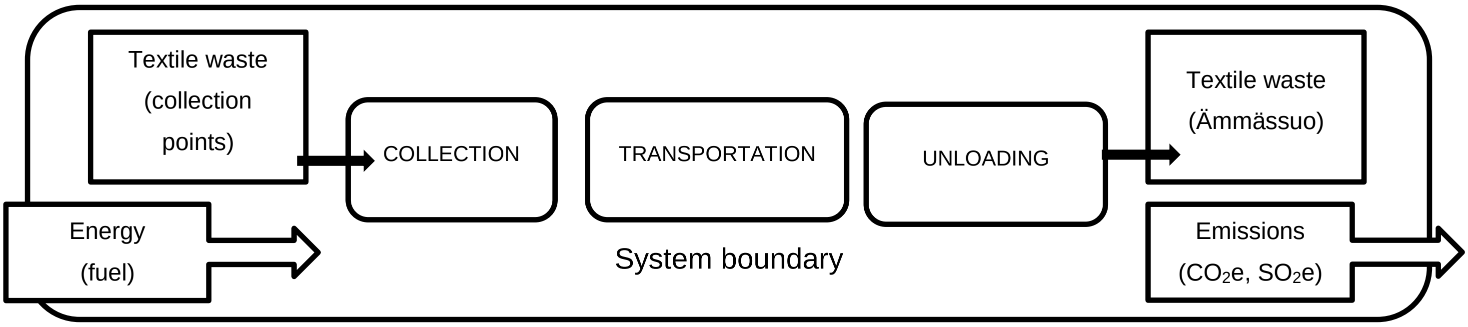

Figure 3. System boundary for textile waste management

The process flow chart for textile waste collection and transportation is presented in Figure 4.

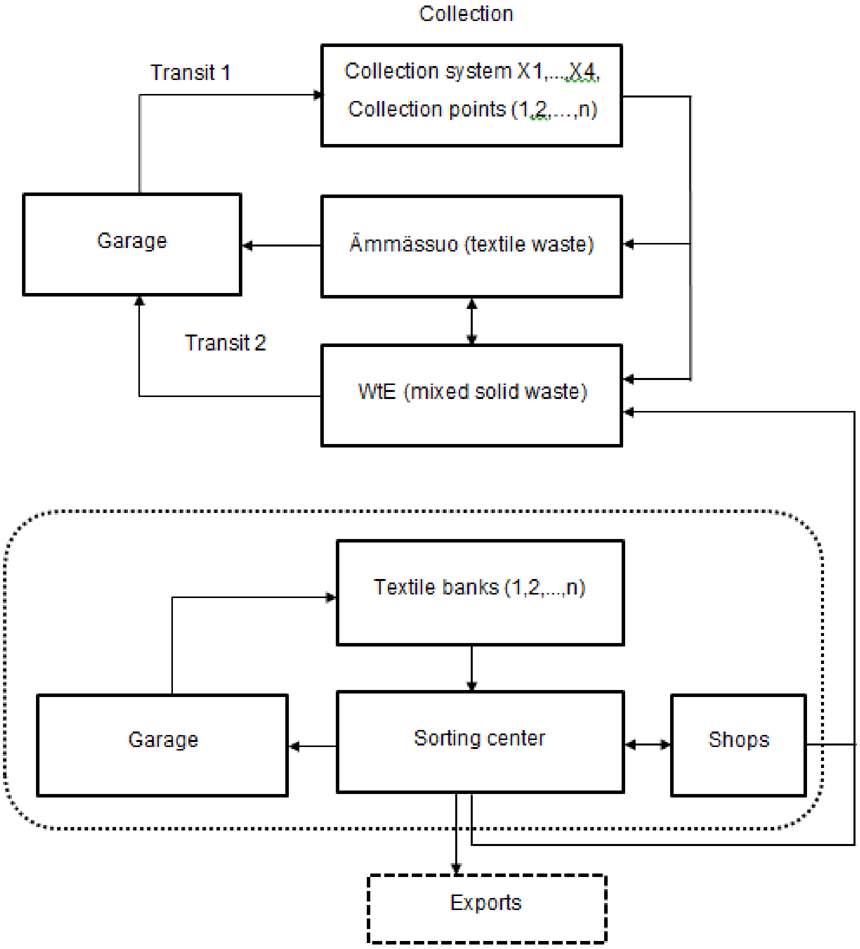

Figure 4. Process flow chart for the product systems for textile waste collection and transportation

The punctuated areas in Figure 3 describes the parallel collection network for used textiles and the paragraph “exports” refers to a product system that is not considered in this study.

3.3 Impact categories and characterization factors

Generally in LCA studies the environmental impact of the studied systems is viewed in three separate endpoints of ecological environment, human health and natural resources (ILCD 2009). Indicator data as provided in the inventory analysis is used to determine the impact in the selected impact categories. The impact categories can be changes in land use, occurrence of accidents, radiation and human toxicity. In this study the number of observed impact categories has been limited to two, climate change and acidification whose impacts are studied at the endpoint of ecological environment.

In this study the indicator for climate change is equivalent CO_2 emissions with the selected emissions species of CO_2, NH_4 and N_2O. The selected emissions differ in terms of lifetime, atmospheric trajectory and global warming potential albeit the effects of these emissions are global regardless of the location of the source (Levasseur et al. 2016, p. 60).

The applied indicator for the impact category of acidification is the equivalent SO_2 emissions with the selected species of SO_2 and NO_x. These emissions are released from the combustion of fuels containing sulphur and nitrogen as trace elements. The ecosystem effects include the increased solubility and activation of both organic and inorganic substances as the pH-levels decrease with the increases in H^+-concentrations in the receiving ecosystems.

Characterization factors are used to calculate specific indices in impact assessment. The indices are used for quantifying the environmental impact in the selected impact categories. In this study the characterization factors are based on values introduced in ENVIMAT 2008- initiative (ENVIMAT 2008; Myllymaa et al. 2008) (Table 6).

Table 6. Applied characterization factors for climate change and acidification

Impact category	Climate change	Acidification
Model	GWP100	AP 100
Unit	kg CO_2e/kg	kg SO_2e/kg
CO_2	1	0
CH_4	25	0
N_2O	298	0
SO_2	0	0.47
NO_x	0	0.17

Characterizing factors determines the impact of a single emission on the impact category potential that can be formulized as follows:

$$IP(V)_m = Q_m * KK(V)_m$$
$$IP(V)_{total\ impact} = \sum IP(V)_m,$$

, where IP = impact potential, V = impact category, Q = emission amount, m = emission species and KK = characterizing factor.

3.4 Scenarios

Scenarios are decision making tools that can be applied to assess the probable outcomes from given conditions. When applied in waste management, scenarios can be used to assess the outcomes of different waste collecting configurations in terms of expected yield and environmental impact. The four scenarios of this study are summarized in Table 7.

Table 7. The scenarios of the study with estimated yields for textile waste recovery

Scenario	Expected yield (tons)
S0 "present state"	0
S1 "recycling points only"	1360
S2 "property-specific only"	1528
S3 "property-specific and recycling points"	2000

Scenario S0 ”present state” describes the present status in used textile collection. In the scenario it is assumed that the yield for used textile remains constant at 1510 tons annually and that there is no parallel collection system for textile waste. The textile waste is assumed to be treated as mixed solid waste in Vantaa WtE plant. Scenarios S1 “recycling points only” and S2 “property-specific only” describes situations in which textile waste is collected in parallel to used textiles and solely at recycling points or from properties. The interaction between the collection systems is assessed in the scenario S3 “property-specific and recycling points”.

3.5 Compensations in textile waste collection

Compensations refer to the possibility to reduce the impact of a given process with different operative alternatives. In the context of this study, the compensations embedded in textile waste collection are studied in terms of replaced production in energy production and avoided consumption of resources in textile material manufacturing. In the case of energy production, it is assumed that the removed energy is replaced with increased production and related fuel consumption in parallel power plants.

3.5.1 Manufacturing of virgin textile fibres

Existing research on cotton and polyester fibres are more extensive than with other natural and synthetic fibres and due to the availability of data the compensations are viewed in terms of the two fibres. The production of a ton of virgin cotton fibres consumes approximately 25000 MJ of energy with the generation of 4.1 kg of CO2-emissions whereas the production of a ton of virgin polyester consumes approximately 126700 MJ of energy with the generation of 8.4 kg of CO2-emissions (Cherett et al. 2005; Ekström & Salomonson 2014). The energy consumption and CO2-emission per ton of manufactured textiles are shown in Table 8.

Table 8. The energy consumption of manufacturing a ton of cotton and polyester fibers and related kg CO2e-emissions

	Per textile ton	
Textile fiber	Energy consumption (GJ)	kg CO_2e-emissions
Cotton	15	2
Polyester	43	3
Total	58	5

Based on the estimated yields in the scenarios, the related energy consumption and equivalent CO_2-emissions for manufacturing the proportions of cotton and polyester are shown in Table 9.

Table 9. Scenario-specific energy consumption and equivalent CO_2-emissions for cotton and polyester

Scenario	Energy consumption (GJ)	kg CO2e
S1	77966	7062
S2	87597	7935
S3	114656	10386

The values were calculated on the basis that the proportion of cotton in the given mass of textile waste accounted for 57 % and the proportion of polyester for 34 %, as was suggested in the study by Schmidt et al. (2014).

3.5.2 Replacement in energy production

In 2015 Vantaa WtE plant utilized approximately 340000 tons of mixed solid waste as a fuel with outputs of 210 GWh (21 %) for electricity production and 825 GWh (79 %) for district heating production (Vantaan Energia 2016). On the basis of the scenario S0, it was assumed that the incinerated waste contained also 10524 tons of disposed textiles. Table 10 lists the scenario-specific given outputs in energy production as the amount of incinerated textile waste varies.

Table 10. Scenario-specific effects in WtE plant outputs

Scenario	WtE production				Replaced production
	Fuel (tons)	District heating (GWh)	Electricity (GWh)	Total (GWh)	GWh
S0	340000	825	210	1038	0
S1	338640	819	208	1030	8
S2	338472	818	208	1029	9
S3	338000	816	208	1027	11
TT *)	339000	825	210	1038	0.006

*) textile waste ton

The scenario data shows that textile waste removal can reduce the expected output by maximum of 11 GWh. It is assumed that the loss in output is compensated with an increased production in other more conventional plants in the grid.

In terms of climate change, the specific CO_2-emissions for district heat production In Vantaa WtE plant was 259 kg/MWh in 2015 (Vantaan Energia 2016), whereas the average emission factor in Finland has been estimated to be approximately 217 kg/MWh (Hippinen & Suomi 2012). In electricity production the emission factor for mixed solid waste is determined as the addition of 31.8 g/kWh with the oxidation number of 0.99 (Energiateollisuus 2017) which is selected to represent the emission factor for WtE electricity production. The average CO_2 emission factor in Finland has been estimated to be approximately i210 kg/MWh (Hippinen & Suomi 2012).

In terms of acidification, the emission factors in Vantaa WtE plant were approximately 345 kg/GWh for SO2 and 406 kg/GWh for NOx (Vantaan Energia 2016). In this study the related emission factor references are taken from HELEN (Helsingin Energia 2017) in which they were 280 kg/GWh for SO2 and 220 kg/GWh for NOx in 2016. In summary, the scenario-specific effects on climate change and acidification are shown in Table 11.

Table 11. Estimated compensations in power production in the selected impact categories

	Climate Change t CO2e			Acidification t SO2e		
Scenario	WtE	Alternative	Compensated	WtE	Alternative	Compensated
S1	1797	2641	-844	5.8	3.9	2.0
S2	2019	2967	-949	6.6	4.4	2.2
S3	2642	3884	-1242	8.6	5.7	2.9
TT *)	1.4	2	-0.7	0.0045	0.003	0.002

*) textile waste ton

4 Inventory analysis

Life-cycle inventory analysis (LCI) contains information about the data, materials and calculation methods applied in the study. In this LCI the scope is limited to the energy consumption, emissions and material and energy inputs of the product system of textile waste collection and transportation. Product system consists of a series of unit processes whose entirety reflects the life-cycle of a given product, process or service by combining material and energy inputs into different impact categories (Koskela et al. 2010). The product systems observed in this study include the textile waste as material, transportation system and the energy recovery of textile waste

4.1 Product system for textile waste transportation

The vehicles are assumed to be compatible with EURO 5 and EURO V emission standards. EURO emission standards are applied to regulate the emission levels of new motor vehicles as stated in the framework directive for the approval of motor vehicles and their technical units (2007/46/EC) (ICCT 2016). EURO 5 and EURO V standards were selected as the operators with more timely equipment is favoured in the HSY waste operator contracts.

There are no official data available on collection routes and the impacts of transportation for textile waste. In this study the energy consumption and emissions of transportation are derived from the LIPASTO emission-database which is an online service provided by VTT Technical Research Center of Finland Ltd (VTT 2017). The selected emissions for the observed impact categories are CO_2, CH_4 and N_2O for climate change and SO_2 and NO_x for acidification. With the lack of more reliable data the average values presented in the database are applied. On the basis of these values, it is assumed that the amount of urban drive in passenger car traffic accounts for 27 % and 70 % in light and heavy-duty trucks. The latter is selected to represent the environmental impact during collection routes. The related LIPASTO-data is summarized in Table 12.

Table 12. Selected LIPASTO-data for textile waste transportation

	Energy consumption		Climate change			Acidification	
	Fuel [l/100km]	Energy [kWh/km]	CO_2 [g/km]	CH_4 [g/km]	N_2O [g/km]	SO_2 [g/km]	NO_x [g/km]
Passenger car (average) EURO 5							
Gasoline	6.2	0.54	136	0.00052	0.00063	0.0007	0.019
Diesel	5.2	0.52	122	0.00016	0.0054	0.00041	0.79
Light truck and van (delivery run) EURO 5							
Empty (2.7 tons)	8.8	0.87	205	0.00048	0.0075	0.00069	0.64
Full (3.9 tons)	10.6	1.05	249	0.00066	0.0075	0.00083	0.77
Heavy-duty truck (delivery run) EURO V							
Empty (15 tons)	18.5	1.83	432	0.00049	0.041	0.0014	2.3
Full (24 tons)	25.6	2.53	598	0.00093	0.044	0.002	2.7

In this study it is assumes that the generic route structure is composed of three different work phases, namely transition drive, collection drive and depletion drive which can be formulated as,

$$R_r = 2T_r + C_r + E_r,$$

, where Tr = transition drive, Cr = collection drive and Er = depletion drive.

The transition drive consists of two events in which the vehicle travels on an empty load from garage to the first collection point at the route and from the waste reception site back to the garage. The total distance travelled during this phase is normalized to 40 km (20 km for each event). The collection drive is the distance travelled from the first collection point to the last during a given route. The total distance varies according to the number of collection points and the distances between the points. During this phase the energy consumption and emissions have been calculated with the assumption that the vehicles cover the drive half-full. The depletion drive is the distance from the last collection point to the waste receiving facility. These distances differ according to the location of the departure point (i.e. last collection point) which has been conventionally fixed to several city centres and Sortti stations. In the case of Vantaa the city contains several centres of which Myyrmäki is selected as a representative due to its central geographical location. The distances between departure points and the waste receiving facilities were determined with the use of browser-based map service provided by Fonecta (Fonecta 2017). These distances are summarized in Table 13.

Table 13. Distances from departure points to the selected waste receiving facilities

	Distance (km)	
Departure point	Ämmässuo	Vantaa WtE
Espoo	9	31
Helsinki	27	18
Kauniainen	11	27
Vantaa *)	27	19
Kirkkonummi	28	51
Sortti-stations		
Kivikko	35	8
Konala	23	22
Ruskeasanta	35	14
Ämmässuo	0	39
Munkinmäki	28	50

*) From the center of Myyrmäki

The applied data for the energy consumption and emissions in transition and depletion drives is shown in Appendix 1. The data contains two separate categories for depletion drive, namely a full load (9 tons) and a load of one tonne (the functional unit).

As a simplified study, it was assumed that emissions during collection and transportation work phases remain constant and proportional to the distance travelled. However, these emissions are affected by the number of accelerations and decelerations performed during a collection route, thus the emissions in property-specific and Sortti station collection can be larger in magnitude than those observed in this study. This aspect should be considered when assessing the results.

4.2 Collection according to the functional unit

4.2.1 Property-specific collection

In property-specific collection textile waste is collected with separate waste containers. The four container volumes observed in this study are 140L, 240L, 300L and 660L, respectively. Table 14 summarizes the estimated carrying capacity and number of containers required in textile waste management.

Table 14. Container-specific textile waste capacity

Container	Volume (m3)	carrying capacity (kg)	Number of containers (pcs.)
140L	0.14	12	80
240L	0.24	21	47
300L	0.3	27	37
660L	0.66	59	17
Average	**0.34**	**30**	**45**

The carrying capacity has been determined by multiplying the container volumes with the density of unsorted textile waste. The number of containers has been determined by dividing the textile ton with the carrying capacity. As the container volumes increase the number of required containers decreases and on average the temporal storage capacity for a textile waste ton requires 45 containers of different volumes.

The distances in transition and depletion drives are assumed to be constant with the only variable being the distance covered in collection drive. In this study the distance between individual collection points is assumed to be fixed at 50 meters and when multiplied with the average number of containers the distance travelled during the collection of a textile waste ton is approximately 2.3 km. The energy consumption and emissions for combined transportation work phases in property-specific collection has been summarized in Table 15.

Table 15. Combined work phases in property-specific collection

	Distance	Energy consumption			Emissions (g)				
Departure point	km	Fuel (l)	kWh	MJ	CO_2	CH_4	N_2O	SO_2	NO_X
Espoo	51	10	93	334	21894	0.03	2	0.07	116
Helsinki	101	13	127	459	30092	0.04	3	0.10	159
Kauniainen	51	10	97	348	22795	0.03	2	0.07	121
Vantaa	67	13	127	459	30092	0.04	3	0.10	159
Kirkkonummi	68	13	129	464	30407	0.04	3	0.10	160
Average	**68**	**12**	**115**	**413**	**27056**	**0.03**	**3**	**0.09**	**143**

The environmental impact for the management of the functional unit in property-specific collection is summarized in Table 16.

Table 16. Environmental impact in property-specific collection.

	Climate change kg CO_2e	Acidification kg SO_2e
Property-specific collection	27.8	0.02

On the basis of the characterization factors applied in this study, the transportation of a ton of textile waste generates approximately 28 kg of equivalent CO_2-emissions and 0.02 kg of equivalent SO_2-emissions.

4.2.2 Recycling point collection

In recycling point collection it is assumed that there is a single container for textile waste whose volume is 1000 litres (1 m^3). In the Capital Region there were approximately 137 recycling points with an average distance of 3 km between the points. This distance has been derived as an average between 20 recycling points located in the Helsinki city centre. On the basis of the container volumes, to gain a textile waste ton requires the emptying of approximately 11 containers. When multiplied with the distance between the points, the distance travelled during collection drive is approximately 33.4 km. The energy consumption and emissions for combined transportation work phases in recycling point collection has been summarized in Table 17.

Table 17. The energy consumption and emissions of combined transportation phases in recycling point collection for a ton of textile waste

	Distance	Energy consumption			Emissions (g)				
Departure point	km	Fuel (l)	kWh	MJ	CO_2	CH_4	N_2O	SO_2	NO_X
Espoo	83	17	163	588	38580	0.05	3	0.13	197
Helsinki	101	20	198	713	46778	0.06	4	0.15	240
Kauniainen	85	17	167	602	39481	0.05	4	0.13	202
Vantaa	101	20	198	713	46778	0.06	4	0.15	240
Kirkkonummi	101	20	199	718	47093	0.06	4	0.15	241
Average	**94**	**19**	**185**	**667**	**43742**	**0.05**	**4**	**0.14**	**224**

The environmental impact for the management of the functional unit in property-specific collection is summarized in Table 18.

Table 18. Environmental impact in recycling point collection

	Climate change kg CO_2e	Acidification kg SO_2e
Recycling point collection	44.9	0.04

On the basis of the characterization factors applied in this study, the transportation of a ton of textile waste generates approximately 45 kg of equivalent CO_2-emissions and 0.04 kg of equivalent SO_2-emissions.

4.2.3 Sortti station collection

The collection drive in Sortti station collection is performed by the customers who deliver the selected waste fractions dirtectly to the stations. At the stations it is assumed that the textile waste is collected in interchangeable pallets with the volume and unladed mass of 16.8 m3 and 2.8 tons and thus the received textile waste ton fits into a single pallet rendering its loaded mass to 3.8 tons. The emissions for transporting this mass have been tabulated from the data in table 13 by assuming that the energy consumption and emissions increases linearly along with the transported mass (Table 19).

Table 19. The energy consumption and emissions of combined transportation phases in Sortti station collection for a ton of textile waste

	Distance	Energy consumption			Emissions (g)				
Departure point	km	Fuel (l)	kWh	MJ	CO_2	CH_4	N_2O	SO_2	NO_X
Kivikko	75	15	147	528	34659	0.04	3.1	0.11	178
Konala	63	12	122	438	28701	0.03	2.6	0.09	148
Ruskeasanta	75	15	147	528	34659	0.04	3.1	0.11	178
Munkinmäki	68	13	132	475	31184	0.04	2.8	0.10	161
Average	**70**	**14**	**137**	**492**	**32301**	**0.04**	**2.9**	**0.11**	**166**

In 2016 the stations received approximately 402780 customer visits who delivered approximately 64900 tons of waste (HSY 2017). This suggests a rough estimation of 161 kg of waste per visit. The customers are assumed to favour stations with the shortest distances and in this study the threshold value has been estimated to be 20 km which are marked as bold in Table 20.

Table 20. Distances between selected departure points and the stations

	Distance to stations [km]				
Departure point	Kivikko	Konala	Ruskeasanta	Ämmässuo	Munkinmäki
Espoo	27	**17**	30	**11**	**20**
Helsinki	**13**	**12**	**20**	32	31
Kauniainen	23	**13**	26	**18**	26
Vantaa	**16**	**3**	**19**	29	38
Kirkkonummi	46	36	49	26	**2**
Distance ≤ 20 km	2	4	2	2	2
Ave.	**16**	**11**	**20**	**15**	**11**

The estimated energy consumption and emissions from the customer visits during 2016 is summarized in Appendix 2. When compared to the total amount of collected waste, the proportion of a textile waste ton accounts approximately 0.0015 % of the delivered waste. When multiplied with the data in Appendix 2 and added to the data in table 19 the combined energy consumption and emissions in Sortti station collection is summarized in Table 21.

Table 21. The total energy consumption and emissions in Sortti station collection for a textile waste ton

	Distance	Energy consumption			Emissions (g)				
Station	km	Fuel (l)	kWh	MJ	CO_2	CH_4	N_2O	SO_2	NO_X
Kivikko	143	19	183	660	43873	0.08	3.2	0.16	179
Konala	108	15	146	524	34772	0.06	2.6	0.12	149
Ruskeasanta	110	17	166	597	39464	0.06	3.1	0.14	179
Ämmässuo	20	1	11	40	2775	0.01	0.01	0.01	0,39
Munkinmäki	78	14	137	495	32539	0.04	2.8	0.11	161
Ave	**92**	**13**	**129**	**463**	**30684**	**0.05**	**2**	**0.11**	**134**

The environmental impact for the management of the functional unit in Sortti station collection is summarized in Table 22.

Table 22. Environmental impact in Sortti station collection

	Climate change kg CO_2e	Acidification kg SO_2e
Sortti-collection	31.4	0.02

On the basis of the characterization factors applied in this study, the transportation of a ton of textile waste generates approximately 31 kg of equivalent CO_2-emissions and 0.02 kg of equivalent SO_2-emissions.

4.3 Touring vehicle collection

In touring vehicle collection it is assumed that the textile waste is collected with interchangeable pallets of the volume and unladed mass of 16.8 m3 and 2.8 tons similar to

Sortti station collection. In 2016 the collection covered approximately 300 properties with the total waste yield of 380 tons (HSY 2017). Assuming the waste is distributed evenly each collection point can deliver approximately 1.3 tons of waste of which the proportion of a textile waste ton is approximately 0.26 %. In 2016 the average distance between collection points was approximately 5 km. The energy consumption and emissions of combined transportation phases in touring vehicle collection is summarized in Table 23. The proportion of the textile waste ton has been derived as the suggested percentage from the total load.

Table 23. The energy consumption and emissions of combined transportation phases in touring vehicle collection for a ton of textile waste

	Distance	Energy consumption			Emissions [g]				
Touring waste collection	km	Fuel (l)	kWh	MJ	CO_2	CH_4	N_2O	SO_2	NO_X
Total waste	5219	1041	10963	39466	2589443	3	220	9	12811
For textile waste	14	3	29	104	6814	0.01	0.6	0.02	34

The environmental impact for the management of the functional unit in touring waste collection is summarized in Table 24.

Table 24. Environmental impact in touring vehicle collection

	Climate change	Acidification
	kg CO_2e	kg SO_2e
Touring waste collection	7.0	0.01

On the basis of the characterization factors applied in this study, the transportation of a ton of textile waste generates approximately 7 kg of equivalent CO_2-emissions and 0.01 kg of equivalent SO_2-emissions.

4.4 Collection according to scenario-specific yields

The scenario-specific environmental impacts are observed in the selected systems of property-specific and recycling point collection as stated in the scenarios. The impacts are assessed based on the assumption that a collection vehicle conducts the depletion run only in a full load (9 tons). The scenario-specific yields and the number of expected depletion runs for a given time period are listed in Table 25.

Table 25. Scenario-specific yields and required depletion runs.

	Yield (tons)		Depletion runs (n)		
Scenario	Property-specific	Recycling points	Year	Month	Week
S1	0	1360	151	13	3
S2	1528	0	170	14	4
S3	1500	500	222	19	5

The environmental impact in the selected impact categories was calculated on the basis of the averages in property-specific and recycling point collection as proposed in tables 16 and 18 above and the impact is summarized in Table 26.

Table 26. Annual environmental impact in scenario-specific collection

Scenario	Climate Change kg CO2e	Acidification kg SO2e
S1	6790	5.8
S2	4745	4.1
S3	7155	6.2

On the basis of the characterization factors applied in this study, the recycling point collection has a higher impact as an individual collection system than property-specific collection due to longer distances between the collection points. The environmental impact in the combined collection is approximately 1.5 times of the impact in scenario S2 according to which the efficiency of gaining an additional yield of 500 tons is more reduced.

4.5 Transportation of textile waste to Vantaa WtE plant

The waste transportation to Vantaa WtE plant describes a parallel transportation system to Ämmässuo waste treatment centre. It was assumed that transported material contains the fractions of textile waste disposed as mixed solid waste. Similarly to scenario-specific collection, the vehicles are assumed to complete depletion runs in a full load (9 tons). The energy consumption and emissions for a single one-way depletion drive is summarized in Table 27.

Table 27. Waste transportation to Vantaa WtE plant

	Distance	Energy consumption			Emissions (g)				
Departure point	km	Fuel (l)	kWh	MJ	CO_2	CH_4	N_2O	SO_2	NO_x
Espoo	31	8	78	282	18538	0.03	1.4	0.06	84
Helsinki	18	5	46	164	10764	0.02	0.8	0.04	49
Kauniainen	27	7	68	246	16146	0.03	1.2	0.05	73
Vantaa *)	19	5	48	173	11362	0.02	0.8	0.04	51
Kirkkonummi	51	13	129	465	30498	0.05	2.2	0.10	138
Average	29	7	74	266	17462	0.03	1.3	0.06	79

Table 28 lists the annual scenario-specific emissions in a situation in which the collection vehicles transports only the textile waste disposed as mixed solid waste.

Table 28. Estimation of annual textile waste transportation emissions to WtE

			Emissions (g)				
Scenario	Textile waste (t)	Depletion runs (n)	CO_2	CH_4	N_2O	SO_2	NO_x
S0	10524	1169	20418431	32	1502	68	92190
S1	9164	1018	17779789	28	1308	59	80277
S2	8996	1000	17453839	27	1284	58	78805
S3	8524	947	16538075	26	1217	55	74670

The average scenario-specific environmental impact for transporting textile waste for energy recovery is summarized in Table 29.

Table 29. Annual environmental impact in scenario-specific textile waste transportations to WtE plant

Scenario	Climate Change kg CO_2e	Acidification kg SO_2e
S0	20867	15.7
S1	18170	13.7
S2	17837	13.4
S3	16901	12.7

The data suggests that with textile waste recovery it is possible to re average reduce the transportation emissions by 3.2 tons for equivalent CO_2 emissions and 2.4 kg for equivalent SO_2 emissions. When compared to scenario-specific textile waste transportations the average net savings are negative approximately -2.9 tons for equivalent

CO_2 emissions and -2.9 kg for equivalent SO_2 emissions. Thus the removal of textile waste from mixed solid waste does not account as savings in terms of transportation emissions.

5 Life-cycle impact assessment

5.1 Comparison of the collection systems

5.1.1 Impact for the management of a textile waste ton

The environmental impact for recovering a textile waste ton in the selected collection systems is summarized in Figure 5.

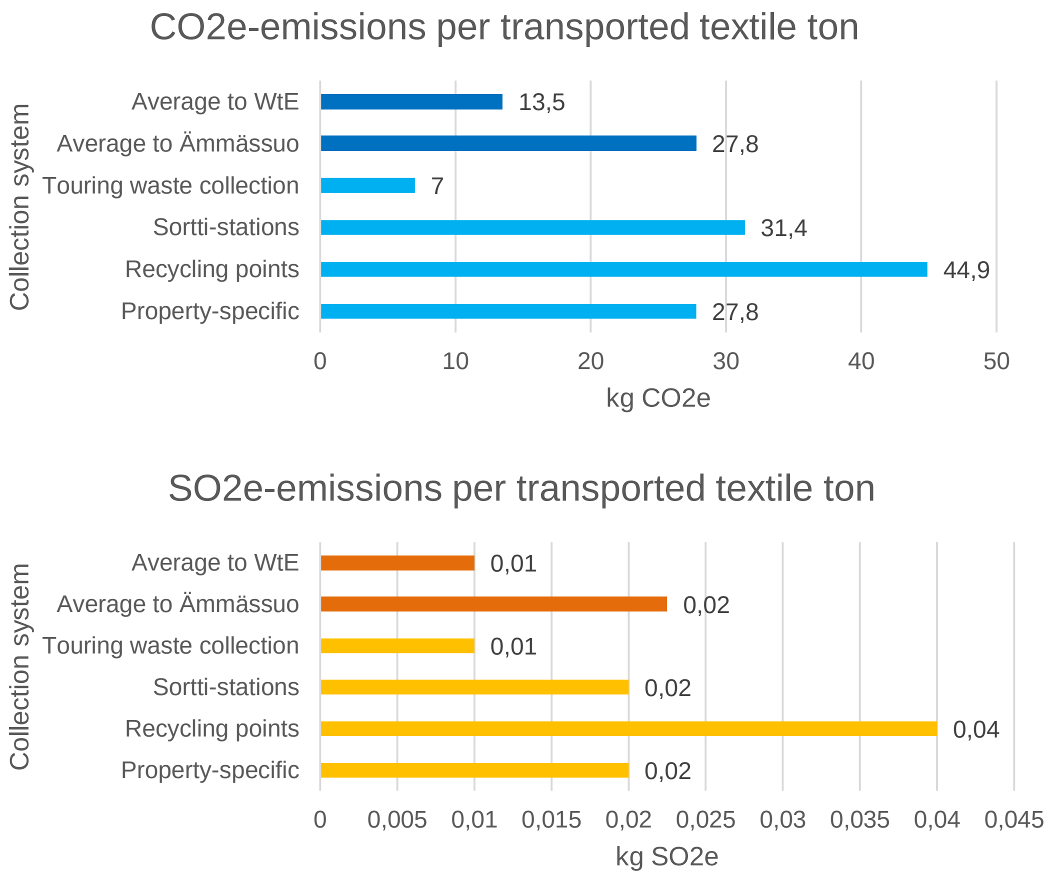

Figure 5. Collection system comparison for the management of a textile waste ton

Figure 5 suggests that the environmental loading in both impact categories is low in touring waste collection and property-specific collection and higher in recycling point and Sortti station collection. When the expected yields are considered, the most effective collection systems are property-specific and recycling point collection while Sortti station and touring vehicle collection remains more like curiosities due to their more challenging availability. As proposed in the transportation route model, the distances travelled during a collection run are shorter in property-specific collection than in recycling point collection thus the disparity in the magnitude in environmental impact per recovered textile waste ton.

5.1.2 Impact in scenario-specific transportations

The scenario-specific environmental impact for transportation is summarized in Figure 6.

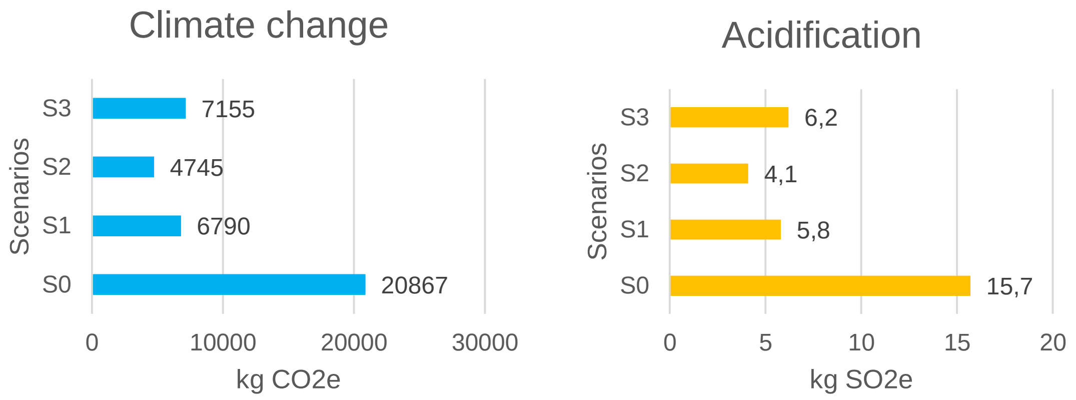

Figure 6. The scenario-specific environmental impacts of waste management transportations

Scenario S0 describes the environmental impact of transporting approximately 10524 tons of textile waste disposed as mixed solid waste into Vantaa WtE plant. In comparison to textile waste collection, the scenario with the least impact is S2 and the scenario with the highest impact is in the combination of the two selected collection systems. When compared to scenario S0, textile waste collection could reduce the equivalent annual CO_2 and SO_2 emissions in WtE transportation by 14.6 tons and 10 kg on average.

5.2 Comparison of compensations

5.2.1 Textile manufacturing

The scenario-specific yields are interpreted as reductions in the production of virgin raw materials. The estimated climate effect for textile waste recovery is summarized in Figure 7.

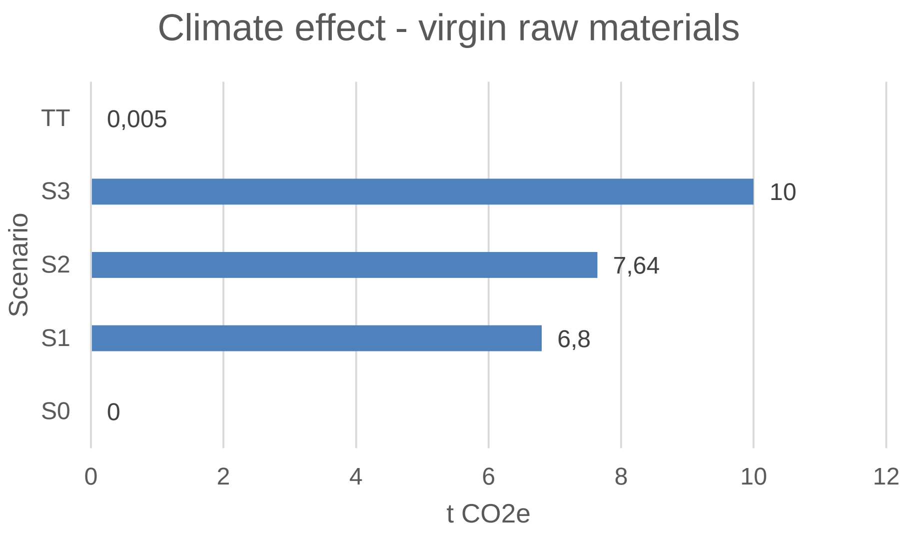

Figure 7. Estimation of avoided equivalent CO_2 emissions in manufacturing

The trend in Figure 7 suggests a linear correlation between the expected collection yields and emissions from manufacturing virgin materials. On the basis of this observation, the scenario with the highest yield (S3) has the potential to reduce the equivalent CO_2 emissions by 10 tons assuming that the collected materials are recycled and utilized to replace virgin raw materials. In comparison to related scenario-specific transportation emissions, the annual net savings are 0.01 tons (S1), 2.89 tons (S2) and 2.86 tons (S3) interpreted as compensations in the product system of textile waste transportation. This means that the climate effect of transportation is positive in the scenarios if the collected material replaces production and the emissions from recycling are less than the proposed net savings.

The acidification effect was excluded from this study due to scarce availability of reliable data. However, as suggested by the study by KEMI (2014) the manufacturing processes involves notable chemical loading and the related acidification emissions can be significant.

5.2.2 Replacement in energy production

The climate effect of replacing the energy content in removed textile waste is summarized in figure 8.

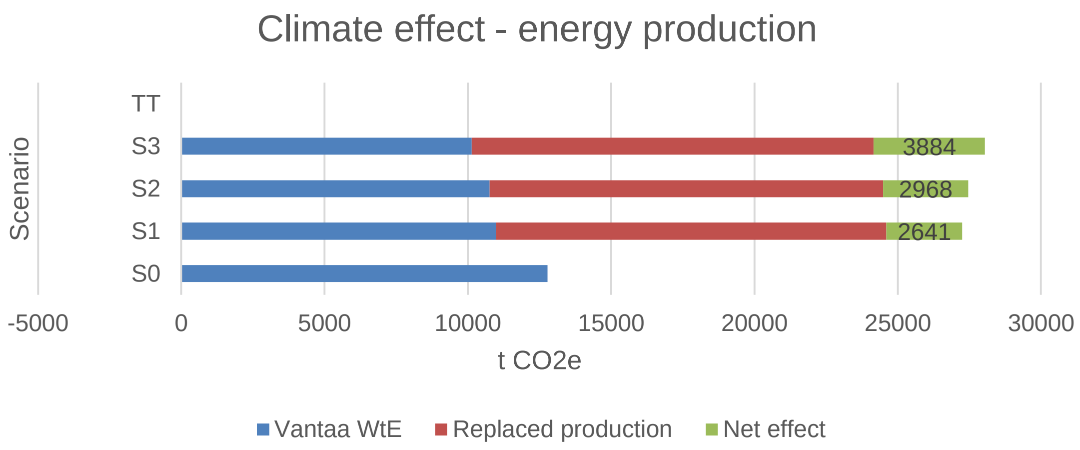

Figure 8. Climate effect due to replacement in energy production

In the scenario S0 it was assumed that there is no removal of textile waste from the incinerated waste and thus no need to replace the lost power output. The trend shows a linear correlation between the collected yield and emission output. As such, the scenario with the most impact is S3 with the replaced energy being the largest of the scenarios. On average, the energy replacement for a textile waste ton accounts for approximately an increase of 0.7 tons in power production in Finland.

The acidification effect of replacing the energy content in removed textile waste is summarized in Figure 9,

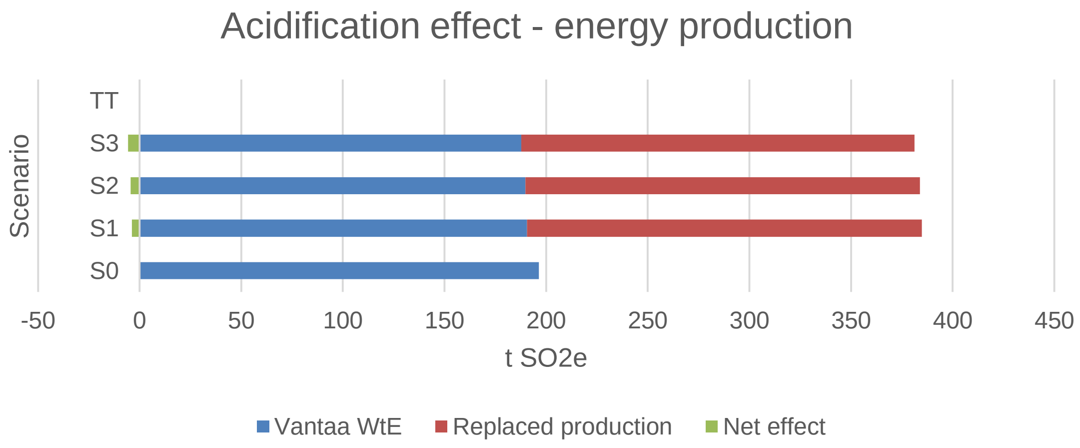

Figure 9. Acidification effect due to replacement in energy production

The removal of textile waste in scenario-specific yields has the potential to reduce equivalent SO_2 emissions in power production. Referring to the correlation between the yield and emission, the largest impact is in scenario S3 with the potential to reduce acidification related emissions by 5.7 tons. On average, the removal of a textile waste ton accounts approximately the reduction of 0.002 tons or 2 kg of equivalent SO_2 emission in power production in Finland.

6 Interpretation

The climate change net effect in textile waste management is negative in the given scenarios and functional unit. On average, the replacements in textile material manufacturing has the potential to reduce annual equivalent CO_2-emissions by 8.1 tons, thus rendering the emissions from collection and transportation phases as neutral. The replacements in energy production yield higher emissions than those resulting from the incineration of textile materials thus contributing as an increase in national CO_2 accounting.

The net effect of acidification in textile waste management is positive. In transportation these emissions are highly regulated as stated in the EURO 5 and EURO V vehicle specifications. In comparison, these emissions are more concentrated in WtE production and thus by reducing the amount of waste being incinerated textile waste collection has the potential to reduce national acidification emissions by the annual average of 4.3 tons.

7 Conclusions

Waste management for textile waste proposes additional costs in terms of economic and environmental performance but on the other hand holds a great promise in terms of increased efficiency in material recovery. The intervention by municipal waste management authorities could enhance the spatial scope of collection and additionally provide a responsible local waste management scheme for textile waste. This involvement would also enhance the role of HSY in national circular economy strategies and achieving the goals stated in the national waste plan proposition. The environmental impacts proposed in the scenarios were rather modest in magnitude. Although the collection provides an additional environmental load, the benefits can be manipulated to supress the nuisances, for example, by favouring wind power in replacement production. In terms of gaining a robust circular model for textiles, the final justification for textile waste collection lingers in the availability of technological capacity and the market demand for the recycled materials.

It should be noted that the models presented in this study are simplifications. They describe textile waste management within proposed parameters and are subjected to deviate from actual circumstances. For example, the actual environmental impact in property-specific and Sortti station collection may exceed those of the two other collection systems. This likely rebound effect can be derived from the higher rate of accelerations and decelerations during individual collection routes. The estimations were based on assumptions and observations from previous studies. They were applied in occasions where there were no data available on textile waste management. Another limiting factor was the simplified structure of the study. By binding variables to their average values, for example, the approach proposed restrictions for the scope of the study.

Prior to any waste collection scheme, a series of pilot projects should be initiated to test the collection potential in realistic conditions. The main focus of these pilots should be in timely and reliable information gathering such as testing yields especially in different property-specific collection configurations based on observed waste accumulation rates and consumer behaviour. When piloting with collection systems, an important consideration would be to reduce overlapping logistics. A valuable approach would be to conduct test runs with vehicles capable of collecting two to four different waste fractions in a single run. Although this would increase the number of required depletion runs due to reduced transportation volumes, these depletion runs would be conducted with a single vehicle instead of using two or four vehicles with longer collection routes per waste. Similarly, a simple container system with inputs for both textile waste and used textiles would serve to purify the feedstock in used textile collection and to increase the yields in waste recovery. Although the infrastructure for the collection can be rather easily arranged, the final factor affecting the robustness of the system is the willingness of the end users to dispose textile waste into designated pathways.

The yields gained in textile waste collection are affected by the accumulation of textile waste, the availability of the collection systems and the willingness of consumers to sort and dispose textiles into designated waste management pathways. Initial collection volumes may remain remarkably below of those proposed in this thesis. Yields are not constant, however, since they can be manipulated with the accessibility of collection points as well as with information.

In terms of efficiency, HSY is the only operator in the Capital Region with a sufficient logistic infrastructure to gain credible yields in textile waste collection. Discarding the availability of proper technologies, the remaining challenges can be summarized as economic and legislative. The annual production volumes in domestic textile industries are rather low in Finland, thus suggesting a generally low demand for recycled textile materials. The possibility for extended producer responsibility (EPR) for textile waste proposes a challenge for municipal waste management intervention. In terms of implementation, EPR has the potential to allocate the waste management responsibility directly to the textile producers, importers and retailers. In such case, the investments made by waste management authorities may suffer reductions in repayment.

Finally, the technical capacity and recycling technologies for textile recovery should be promoted and developed in Finland although the establishment of an industrial-scale recycling centre might seem unlikely. The global demand for efficient technical solutions is on an increase, thus providing a proper niche for technological exportation. Advances gained in the Relooping Fashion initiative proves that the technical recycling capacity in Finland is developing and brewing into more robust solutions. Furthermore a scheme to close the loop for textiles can provide valuable insights in other national recycling ventures thus allowing an efficient leap-frogging to occur. To tackle the challenges related to textile waste demand, yield and regulations the possibility for Nordic cooperation should be considered. This cooperation could assist to reduce the burden of individual authorities and result in further advances in textile waste recovery and economical utilization strategies.

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Appendix 1. Energy consumption and emissions in transition and depletion drives

Unit process	Load Tons	Distance km	Energy consumption Fuel (l)	kWh	MJ	Emissions (g) CO_2	CH_4	N_2O	SO_2	NO_x
Transition drive	0	40	7	73	264	17280	0.02	1.6	0.056	92
Depletion drive	9									
Espoo		9	2	23	83	5442	0.01	0.4	0.018	25
Helsinki		27	7	69	249	16325	0.03	1.2	0.055	74
Kauniainen		11	3	28	101	6638	0.01	0.5	0.022	30
Vantaa *)		27	7	69	249	16325	0.03	1.2	0.055	74
Kirkkonummi		28	7	71	255	16744	0.03	1.2	0.056	76
Average		21	5	52	187	12295	0.02	1	0.04	56
Depletion drive	1									
Espoo		9	2	17	62	4099	0	0.4	0.013	21
Helsinki		27	5	52	187	12297	0.01	1.1	0.04	64
Kauniainen		11	2	21	76	5000	0.01	0.5	0.016	26
Vantaa *)		27	5	52	187	12297	0.01	1.1	0.04	64
Kirkkonummi		28	5	53	192	12612	0.02	1.2	0.041	66
Average		21	4	39	141	9261	0.01	0.8	0.03	48

*) From the center of Myyrmäki

Appendix 2. The number of customer visits to Sortti stations with estimated transportation related energy consumption and emissions.

	Customer visits	Distance	Energy consumption			Emissions (g)				
Station	2016	km	Fuel (l)	kWh	MJ	CO_2	CH_4	N_2O	SO_2	NO_X
Kivikko	138328	4398830	272727	2375368	8551326	598240934	2287	2771	3079	83578
Konala	132355	2898575	179712	1565230	5634829	394206132	1507	1826	2029	55073
Ruskeasanta	58221	2293907	142222	1238710	4459356	311971406	1193	1445	1606	43584
Ämmässuo	44462	1324968	82148	715483	2575737	180195594	689	835	927	25174
Munkinmäki	29416	647152	40123	349462	1258063	88012672	337	408	453	12296
Total	402782	11563432	716933	6244253	22479312	1572626738	6013	7285	8094	219705