Textile production accounts for 10% of the world’s carbon emissions, is reportedly the second most polluting sector in the world and represents a complex, problematic waste stream. Outside of well-established reuse markets and mechanical recycling processes (where capacity limits exist), there remains a large quantity of low-value materials for which there is no market pull to utilise. A potential solution is the development of innovative chemical recycling technologies for textile materials, an area of which is being addressed by the H2020 project RESYNTEX.

Developing markets for the lowest grade textiles can have wider benefits, including supporting the sorting process and RESYNTEX is working on a recycling technology to enable low-value blended textiles to be separated and processed into feedstocks for the chemical industry. Knowledge of the markets (EU-wide) considered as inputs (residual textiles) and outputs (chemical products) for the process has been quantified to identify the overall opportunity, alongside technology development.

In the context of textile waste, there are a variety of types and specifications and there is not a ‘one size fits all’ model for reuse or recycling. Whilst RESYNTEX is focused on residual textile waste, there are notable examples of wider activity in chemical recycling technologies for textiles. This includes Worn Again, Ioniqa, Lenzing, Re:newcell and Evrnu™ to name a few. Encouragingly, partnerships are being seen between brands and innovators to move this technology closer to a commercial reality, providing opportunities for specific types of textile waste.
1. **Introduction**

There is much discussion within the fashion and wider textiles industry regarding the overall sustainability and environmental impact of textile products and garments. The move to a Circular Economy is becoming more widely discussed and adopted, largely thanks to its recognition achieved through the work of the Ellen MacArthur Foundation (1). The impact of textiles on the environment is well documented: that the global production of textiles accounts for 10% of the world’s carbon emissions demonstrates a clear need for solutions to reduce or help prevent this problem from worsening (2).

A ‘circular’ approach to textiles involves moving away from our traditional ‘take, make and dispose’ model and working to achieve a model whereby fibres/fabrics/garments are kept in use and at their highest value. The ability to recycle textiles fibre-to-fibre (e.g. polyester from used/worn textiles back into polyester to make new textiles) is of particular interest.

The focus of this paper is the secondary textiles market - one which has a long history, and in which higher quality items are the most sought after due to their value and potential for export and resale.
either inside or outside the European market. Ensuring that there are markets for secondary textiles to be processed reduces the amount of textiles which end up in landfill or incineration without energy recovery, hence improving the ‘circularity’ of these valuable items. As the quality of secondary textiles decreases, the options available become of less value, as highlighted in Figure 1.

*Figure 1 Textile waste hierarchy*

Currently, for ‘residual’ textiles which are contaminated, damp, ripped or stained and are no longer wearable, disposal commonly consists of landfill or incineration (without energy recovery) as there are no other valorization routes available. It is this type of waste for which research is being conducted to try to reduce or eliminate the disposal costs which are incurred and the environmental burden of landfill and incineration without energy recovery. It is important to find innovative solutions to valorize this waste to ensure that it does not add to the already significant environmental impact created by textiles.
2. Aims and Objectives

The aims of this paper are two-fold. Firstly, to estimate the quantities of residual textile waste across the EU-28 which could be suitable for the RESYNTEX process, as well as to provide information on the markets for outputs of chemicals which are expected to be produced from the process. Secondly, the paper investigates wider sorting and recycling technologies which are under development and provides commentary on the opportunity for commercial availability.

The objectives, therefore, are divided into two parts:

Part 1: Current quantities of waste textiles suitable for the RESYNTEX project and market information relevant to the chemical outputs produced.

- To estimate quantities of residual textile waste from a variety of sectors in which textiles are found across the EU-28.
- To determine, where possible, the composition of residual textile waste in the Member States generating the highest volumes.
- To determine the current market conditions for each of the chemical outputs being investigated by the RESYNTEX project.

Part 2: Industry developments in sorting and recycling technologies for textiles.

- To investigate and report on wider industry developments around technologies for chemical recycling for textiles.
3. Methodology

Research for this paper was carried out through primary and secondary research, mostly via desk-based information-gathering and by conducting interviews with key stakeholders.

Primary research was conducted through semi-structured interviews with collectors and sorters of textiles in Europe trading in used textiles. Data collected were anonymized and aggregated to ensure participant confidentiality.

Secondary research was carried out through extracting relevant data on textile waste from a variety of sources which included Eurostat, Comtrade and the European Apparel and Textile Confederation (EURATEX) databases. Secondary research also included information-gathering on the market situation for the chemical outputs being produced through the RESYNTEX project and a literature review on developments within the wider field of textile recycling technologies.

4. The RESYNTEX process: an overview

RESYNTEX is a H2020 project (3), launched in June 2015 with the ambitious aim of using industrial symbiosis to produce secondary raw materials from unwearable textile waste (4). The waste primarily targeted by the process is residual textile waste, for which there are currently few or no end-of-life options with a marketable value. The RESYNTEX process is working to convert this residual textile waste into feedstocks for the chemical industry, namely:

- proteins, derived from wool – for use in wood-based adhesives,
- glucose, derived from cotton – for conversion to bioethanol,
- monomers from polyamide – recycled back into polyamide, and
- monomers from polyester – recycled into polyethylene terephthalate (rPET).
a. RESYNTEX inputs: Residual textile waste by sector in the EU-28

Seven sectors were investigated as part of our research for the RESYNTEX consortium: clothing, carpets, mattresses, furniture, uniforms, vehicles and textile manufacturing waste. Across these seven sectors, the total amount of textiles being landfilled or incinerated in the European Union was quantified at 9.35 million tonnes.

The waste streams below were evaluated as having the most potential for the RESYNTEX process:

- clothing and household textiles,
- uniforms, and
- mattresses.

The complex waste streams from furniture, end-of-life vehicles, textile manufacturing and carpets were not considered in detail for a variety of reasons including: inaccessibility (without changes to current collection/sorting procedures); competition (commercially available recycling options already exist); and economies of scale (only low-to-medium concentrations of textiles are found in the waste).

It was outside the scope of the RESYNTEX project to develop a pre-sorting step to remove contaminants and increase potential accessibility, which also informed the reasons for not investigating all the sectors in detail. Therefore, for the purposes of this paper, only the findings for the three sectors identified as having the most potential are reported.

**Clothing and household textiles**

Clothing and household textiles are a complex input material for the RESYNTEX process due to the variation in their composition, their quality at the point of disposal and the existence of alternative markets for textiles which have been recovered. Treatment options largely depend on whether the items have been segregated: if there has been no segregation and the items are mixed
with non-textiles and are contaminated, there is little choice but to landfill or incinerate, unless it is possible to implement a pre-sorting step. It is also unlikely that textiles will be recovered if they are placed in mixed household waste. It was estimated that 5.68 million tonnes of residual textile waste are produced by this sector. Not all of this waste is going to be accessible to the project; based on the data gathered from interviews of textile collectors and sorters, the amount of residual waste available to RESYNTEX is approximately 80,000-100,000 tonnes.

*Figure 2 Flow diagram of EoL clothes from source to treatment*

There are both challenges and opportunities arising from this type of waste for the RESYNTEX project. The single biggest opportunity lies in valorizing textile waste and creating competitive chemical outputs which have market value. The challenges are the consistency of the input materials, the sorter capacity in Europe, and the current struggle to deal with contaminants.

**Uniforms**
For this study, uniforms were defined as items of clothing provided to staff by their employer, and include the following categories:

- workwear,
- protective clothing,
- career wear, and
- corporate casual/leisure wear.

The most recent estimates for the volume of uniforms which are disposed of annually in the EU-28 indicate that approximately 70,000 tonnes are landfilled or incinerated with energy recovery. This is a large amount which could be diverted towards the RESYNTEX process.

**Figure 3** Flow diagram of EoL uniforms from source to treatment

Uniforms present a significant opportunity for chemical recycling, mainly because they can be collected via a ‘take-back’ system, because of the consistency of the fibres which are used, and due to the semi-predictability of supply as a consequence of company re-brands or regular uniform refreshes. The challenges in collecting this type of clothing will be in streamlining collection of
uniforms and the ability to transport them to a location where chemical recycling is available, as well as ensuring that components and/or contaminants are removed.

**Mattresses**

Mattresses are typically large items and are made up of various different materials which makes their disposal complex for waste contractors. Transport over long distances can be uneconomical for mattresses due to their high volume-to-weight, and these bulky items also require a large amount of space (ideally undercover) for storage prior to recycling. Nevertheless, there are examples of mattress recycling activities already taking place, and approximately 30,000 tonnes of mattress waste are currently being recycled. The residue - approximately 270,000 tonnes of waste - could be diverted towards the RESYNTEX project.

*Figure 4 Flow diagram of EoL mattresses from source to treatment*
Mattresses do present a challenge not only in terms of their size and the options available for transport and storage before recycling, but also because they are multi-component products (that could be contaminated or damp) which require an amount of manual processing to extract the required materials at the end of life. However, if these challenges can be overcome, there is an opportunity to establish an end-of-life market for the textile components in mattresses - as there is for other mattress components. The quantity of waste which would be diverted from landfill is also significant – 270,000 tonnes.

b. RESYNTEX outputs: market analysis

The market conditions for the four target chemicals being produced by the RESYNTEX process were analysed to determine current market performances and trends.

Proteins

Overview

Proteins can be extracted from wool and silk fibres. It is reported that it can be difficult to extract proteins from wool, and that using traditional methods only 50-60% extraction is possible (5). Keratin is a protein found in animal nails, horns, wool and hair, with wool being made up of approximately one third keratin. Over 50% of the global keratin market is in personal care and cosmetic products, for which there is a growing demand (6,7). Growth is forecast in the Asia Pacific market in particular, due to lifestyle changes in countries including Japan, India and China. With a predicted growth in the keratin market globally, this presents an opportunity for RESYNTEX to tap into the market if keratin can be produced at a suitable level of purity from waste textile fibres (wool) and the end product offered at a competitive price. The presence of
impurities in the amino acids solution produced by the RESYNTEX process would have a direct impact on the suitability of extracted keratin for its use in the cosmetic and personal care market.

**Market for textile-derived wood adhesives**

Textile-derived proteins are just one of many non-petrochemical alternatives being investigated. Ideally, hydrolysed proteins - regardless of their origin - will produce a relatively similar mixture of amino acid fragments. Keratin can have a higher sulphur content than a typical bio-derived protein mixture, because of its high concentration of disulphide bonds which crosslink the proteins together into filaments. The market competition includes petrochemical and bio-based wood adhesives, both of which (but the petrochemical source in particular) can achieve economies of scale that would be unrealistic for textile waste.

**Glucose - bioethanol**

*Overview*

Cotton fibres typically consist of 88-96% cellulose (8), making them an ideal candidate to convert to bioethanol through hydrolysis and fermentation. Cellulosic fibres (such as cotton) can be converted into glucose through a hydrolytic process, and research carried out by Irfanullah *et al.* concluded that, at optimal conditions, a conversion of 21-39% cotton to glucose can be achieved (9). The glucose produced using hydrolysis was reported in the Irfanullah study as being suitable for end uses including bioethanol production (by fermentation) and bacterial cellulose production. A study by Badger in 2002 also commented on the emergence of cost effective technologies for producing ethanol from cellulose (10). Should the RESYNTEX process be able to access sufficient cellulosic fibres, previous studies suggest that the process can be carried out cost-effectively.
**Markets for bioethanol**

Globally, there is an increasing demand for ethanol-derived products. This includes industrial solvents, cleaning agents, disinfectants, preservatives, fuels and gasoline additives, as well as fuels themselves (11). Therefore, the production of bioethanol from textile waste appears to have a readily accessible market.

The biggest markets in the EU for renewable ethanol are:

- fuel,
- food and beverages, and
- industrial products.

Market data are available from the European Renewable Ethanol Association (ePURE), whose members represent approximately 90% of the total ethanol production sector in Europe. ePURE members were reported to be producing 7.8 billion litres of ethanol in 2014, with an estimated total European production capacity of 8.8 billion litres (12). France and Germany are the two largest producers of ethanol, manufacturing 1 billion and 750 million litres per year respectively (13). These are likely to offer the greatest competition to production from a future RESYNTEx process.

**Polyamide monomers**

*Overview*

Polyamide is a polymer in which the monomers are linked via amide groups, and can be derived from natural or synthetic sources (14). Synthetic polyamide is sold globally, most commonly as nylon in nylon-6 or nylon-6,6.

**Markets for polyamide monomers**

Polyamide is used in a variety of sectors including:
- Clothing and textiles - nylon.
- Electronics - in the plastic housing of power tools and electric switch housings.
- Packaging - in boil-in-the-bag food packaging and other food packaging where low gas permeability, toughness and temperature resistance are required.
- Machinery - in gears and bearings where self-lubricating properties are a benefit.
- Consumer goods - in cable ties, fishing lines and carpets.
- Coatings - corrosion resistant coatings for industrial applications.
- Automotive - in extruded components ranging from door handles, radiator grilles and engine components (15,16).

Figures available from 2013 indicate that Europe produces approximately 700,000 tonnes of polyamide-6,6 and 1.2 million tonnes of polyamide-6, accounting for 21% and 28% of global annual production respectively (17). Against a 7% global year-on-year growth, production of polyamide is expected to grow strongly in China over the next five years and is forecast to account for approximately 40% of the global polyamide production (18). An increase in production capacity for polyamide is expected at around 7% per year. With growth in the market predicted for China, this is anticipated to have an impact on the rest of the market and affect imports of polyamide into the country.

The use of polyamide in the automotive sector is the largest and data from 2015 indicates that 36% of the nylon resin consumed was used in this sector, with growth predicted at around 2.5% per year for the next five years (18).

The current global market for polyamide is projected to reach a value of USD 43.77 billion by 2020 and grow at a CAGR of 5.4% between 2015 and 2020 (16). The largest share of this growth is forecast to come from the automotive sector where an increase in polyamide use in the manufacture and production of lightweight vehicles is expected. On a global scale, the USA is the largest
producer of polyamide. Within the European market, most polyamide production takes place in Germany, the Netherlands and Italy (19).

In Q3 2016, producers of nylon-6 in Europe have reported negative margins; the problem is capped European prices compounded by an over-supply of approximately 200,000 tonnes/year (20). The forecast for growth in the polyamide market in 2016 is approximately 5% due to weak margins. Key players in the sector in Europe have reported that their summer shutdowns could last longer than usual for these reasons, despite there still being strong demand from end users.

Polyester monomers

Overview

Polyester, when used to refer to a textile, denotes a specific polymer called polyethylene terephthalate (PET). 1 Polyester is the premier textile fibre globally, accounting for approximately 45 million tonnes and 58% of all fibres produced (or 80% of all synthetic fibres produced). PET is also used in films, food packaging, plastic bottles and other applications. It can be produced either by a transesterification reaction with ethylene glycol and dimethyl terephthalate; or by an esterification reaction with ethylene glycol and terephthalic acid (the major route). Both these processes proceed via a bis(hydroxyethyl) terephthalate (BHET) intermediate, which undergoes condensation to make PET. At this point, extruded as granules, the PET has a low molecular weight (as measured by intrinsic viscosity) and is suitable for applications such as fibres and films. Further condensation processing is required to increase viscosity for the production of bottles (bottle grade PET) or technical yarns (fibre grade PET).

1 More generally, polyesters chains of monomers (repeating molecules) which are held together by ester linkages
**PET recycling**

PET plastic bottles and packaging are widely recycled in Europe. It is an attractive waste stream for recycling because of its homogeneity and the value of the recycled products. Bottle- and packaging-derived PET can either be recycled mechanically (21) or chemically (22); mechanical recycling has the lower environmental impact of the two, but is only suited to smaller scale operations. PET from recycled sources is often referred to as rPET and it has its own distinct market. Some corporates and brands prefer rPET to PET because of its lower environmental impact compared to virgin polymer. Bottle producers are also targeting higher rPET content in their products, though this is highly contingent on the quality of the rPET they can obtain (23).

Chemical recycling of PET involves the destruction of the polymer structure to release the starting (or intermediate) chemicals used in PET production. Processes are complex, so chemical recycling is best suited to large-scale PET recycling. Mechanical recycling involves washing and grinding bottles to produce flakes that can be blended with virgin polymer to produce (in general) lower quality products. Mechanical recycling has a lower environmental impact than chemical recycling but is less suitable for very large scale operations.

Mechanical recycling is also used to describe processes by which fibres from waste textiles are separated and reformatted using pressing, cutting, pulling and carding etc. to create new textiles. Because of the degrading effect on textiles these reformatted products are invariably of lower quality and find use in (e.g.) felts, mats, acoustic and thermal insulation.

**Polyester textile recycling**

The recycling of polyester textiles, though chemically the same material as in PET bottles and packaging, is complicated by a number of factors. The most important is that current recycling
technology cannot process fibre blends. A fuller list of barriers to polyester fibre recycling includes:

- Polyester is blended with other fibres, predominantly cotton, in fabric items.
- Buttons, zips and other components need to be removed from clothing articles.
- There are chemically different polyesters, including PCDT (poly-1,4-cyclohexylene-dimethylene terephthalate), which are difficult to differentiate from PET.
- Fibre-grade PET is less valuable than bottle or food packaging grade PET.

In the particular case of pure (PET) polyester textile streams, both chemical and mechanical recycling is possible. Patagonia, the outdoor-clothing brand, sorts returned end-of-life clothing and sends the polyester textiles to the Japanese chemical recycling facility Teijin (24). This process is not cheap: the recycled polyester produced by Teijin costs 10% more than virgin polyester because of the additional pre-processing steps required to reduce contamination, even when Patagonia considers recyclability at the design stage of its products (25). Mechanical recycling is also possible where, similar to PET bottle recycling, the textile is shredded and granulated into polyester chips to be melted and spun into new filament fibres. Alternatively, the polyester can be used to make lower quality unwoven materials such as is used in construction, the automotive industry and geotextiles.

**Markets for rPET**

The rPET on the market is nearly wholly derived from PET bottle recycling. It is typically traded as bottle flake (shredded and washed bottle fragments) or pellets (extruded PET ready for re-melting to produce new products); colour and chemical impurities are the key determinants of quality.
rPET typically trades at about a 15-25% discount to virgin PET, the price of which tracks that of crude oil: though not directly linked to oil, in periods of low oil price the price of rPET drops to stay competitive with virgin PET; in periods of high oil price, the interest in - and thus the price of - rPET increases. Overcapacity in rPET production in some parts of the world, including the USA, is driving down prices to such an extent that the introduction of anti-dumping tariffs is being considered (26).

In 2014, the PET packaging collection rate climbed to 57% (from less than 5% in 2001) and a total of 1.7 million tonnes of PET was recycled, utilising 79% of the PET recycling capacity of Europe (27). An estimated 50% of waste plastic from Europe (including PET) is exported, with China dominating global plastic bottle and flake imports (28).

Improvements in PET mechanical recycling processes, including optical sorting, have resulted in much lower levels of contaminants in the recycled products, meaning more value can be retained and proportionately less rPET is being down-cycled into lower quality materials, including textiles.

5. **Industry developments in textile recycling**

In recent years, there have been collaborations between brands and innovator companies, with the overall aim of developing recycling technologies which deal with the textile waste problem. With the increase in clothing consumption, greater amounts of textiles are being discarded, some of which having hardly been worn. This section of the paper reports on opportunities by those in the industry to work together to address this problem and find a solution.

Blended textiles pose a particular problem when it comes to textile recycling, with the separation of blends being a significant barrier. The common use of polyester and cotton blended together creates a high proportion of fabrics on the global market in which each component cannot currently be separated and extracted for recycling. To overcome this, Worn Again has recently partnered
with H&M and the Kering Group to address the difficult issue of blended polyester and cotton in end-of-life textiles. The Worn Again process aims to be able to separate polyester and cotton and enable both fibre types to be ‘recaptured’ and spun into new yarns and fabrics (29). This would enable these fibres to move towards a much more circular model in the future to save valuable resources from becoming waste.

To deal with the specific problem of polyester, Ioniqa Technologies has developed a recycling solution for PET which can accept coloured polyester into the recycling process (30). The company plans to have a 10,000 ton production plant in operation during 2017 – an ambitious and potentially game-changing announcement for the textile recycling industry. Should this be successful and should Ioniqa be able to access sufficient quantities of waste textiles, this could divert a large proportion of textile waste from its current disposal routes. Having the unique selling point of being able to remove colour from PET plastic efficiently and cost effectively could set this technology apart from others being developed and create a model whereby PET can be recycled again and again (31).

A partnership which could see up to 48 million garments produced from 3,000 tons of textile waste has been struck between the Inditex Group and Lenzing (32). As part of this unique approach between the two companies, the Inditex Group will begin to integrate collection points in Spain’s major cities, reportedly up to 2,000 across the country (33). Whilst this technology is focused on cellulosic waste, it highlights the importance of getting brands, suppliers and manufacturers to work together. In some ways, the brand has greater influence over the feedstock and its availability (incentivizing and making return of old clothing easy for consumers), whilst the supplier / manufacturer is in a position to ensure that the returned clothing is responsibly recycled. At-home collection of used clothing will also be available to customers of Zara (part of the Inditex group)
when online orders are delivered, thus making returning of clothing (and increasing feedstocks available) easier for consumers (34).

Focusing on cellulosic fibres such as cotton and viscose, Re:newcell is reportedly in the process of setting up a recycling plant in Sweden which is expected to work to a capacity of 7,000 tonnes/year (35). This would create a large capacity for recycling cellulosics in northern Europe which could reduce transportation of used textiles from this part of Europe, as well as accept textiles from across Europe to maximize capacity. Re:newcell has already (2014) showcased a garment made using recycled fibres from its process, which was hailed as a breakthrough for the industry (36).

American-based technology company Evrnu™ claims to have invented “the only regenerative fiber made from post-consumer cotton textile waste” (37). The technology is patented and converts solid waste into liquid to enable new fibre to be formed. The innovative start-up has partnered with Levi Strauss & Co. to create jeans using fibres from five discarded t-shirts (38). The aim is to create a pair of Levi jeans made from recycled fibres which is as strong and durable as those made using virgin cotton fibres. In terms of overall sustainability, huge savings on water (98% when compared to virgin cotton fibre production) are reported to be made when using this new technology. This clearly shows potential, and the collaboration of a retailer with the history and prestige of Levi Strauss & Co. indicates the quality of this process and its ability to meet stringent performance requirements for consumers who expect the highest of qualities from such a brand.

6. Conclusion

The research carried out for this paper has shown that there are significant quantities of residual textile waste which are being created in Europe with a growing need for routes these from landfill and incineration at the end of life. There is a variety of waste streams in which textiles are found and these have potential to be available for specific recycling processes e.g. RESYNTEX.
Chemical recycling appears to be providing some solutions to this problem. Whilst chemical recycling processes are currently at the developmental stages, it is not unreasonable to consider that some of these solutions will be available to the market on a commercial scale within the next 5-10 years.

It is encouraging to see partnerships being formed between brands and innovator companies taking steps to move recycling technologies for textiles forward and ever closer to becoming a commercial reality.
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