A CIRCULAR ECONOMY PARADIGM FOR TOTAL WASTE TEXTILE REFINING

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ABSTRACT
The paper presents the new circular economy paradigm featuring the first total textile chemical recycling process developed in the course of the European research project RESYNTEX. The process development follows several process modelling and process integration stages making use of conventional and new process optimization tools. Energy and water integration play an important role in the design procedure but emphasis is given to the extended application of Industrial Symbiosis practices to attain the desired sustainability characteristics for the process. It is shown that positive cash flow is possible but still additional incentive is needed to justify the large capital expenditure.

INTRODUCTION
Industrial Symbiosis is a merely networking practice. It features the use of waste streams as resources to other industries and constitutes the essential part of the Industrial Ecology. It promotes closed life cycles by integrating energy and material flows and it differs from recycling and often preferred over it by offering smaller footprints along smaller paths for the energy and material exchanges. Several waste streams/reasons have led to the rise of renewable decarbonised economy transformation, leading to additional advantages such as direct, indirect employment, local business opportunities, improvement in natural resource use (sustainable production & consumption), expanding currently known product portfolio and chemistries derived from fossil fuels. Textile Waste reaches globally 0.1 billion tons and the textile market size expected to reach USD 1,237 billion by 2025. In Europe - the largest consumer market and the second biggest producer in the world - the textile industry employs 1.7 million people with a turnover of EUR 166 billion. Given that up to now, the flow of 60 Mt of natural and synthetic textile polymers follow the trajectory of the linear economy from natural resources extraction to polymer production, textile manufacturing and eventually waste disposal, there is clear incentive for exploring the possibility of integrating the flows of waste textiles into a novel circular economy concept. This, is possible through open loop recycling that taps into the strengths of industrial symbiosis. However, the task has to overcome a number of challenges. First there is no integrated process in place to recuperate holistically the waste textile. There is regional and seasonal variability in waste textile composition raising feedstock standardization issues. Waste textile collection schemes are not widely established and the supply chain bears high logistics costs due to low bulk density. Also, the dye removal process can often be very costly and significant innovation is required in the waste textile product purification processes. The RESYNTEX textile refinery paradigm addresses most of these challenges and is presented next in the context of the Circular Economy enabled by the industrial symbiosis approach used for the integration studies. Results of the analysis are then presented followed by conclusions and suggestions for the way forward.

THE RESYNTEX PARADIGM
The chemical recycling of pure fibres is already conducted commercially, but there is no real application able to recycle blend fibres other than the process of RESYNTEX project. The Total Textile Waste Refinery (TTWR) is a new textile waste recycling and refining process being currently developed in the course of the European Horizon2020 research project RESYNTEX. It involves 20

partners including industrial associations, SMEs, research institutes, universities and applies more than 20 conversion chemistries to transform waste textiles into chemicals. The experimental concept is currently being upscaled to an integrated pilot facility that will undergo optimization and validation of the technology in an industrially relevant environment. RESYNTEX uses the complete spectrum of waste textiles as feedstock, aiming to provide a holistic response to the largely overlooked waste textile management problem. TTWR is now just before the phase of pilot construction and process integration technologies are currently implemented to accelerate the design solution. TTWR consists of gate links between textile materials with commodity and specialty products and chemicals. The value chain of RESYNTEX includes the feedstock that contains the entire range of textile fibres and final products including bio-ethanol, adhesives used in the wood-based panel production, PET bottles and PA-derived value-added chemicals (see Figure 1).

PROCESS DEVELOPMENT

The problem is how to integrate standalone chemistries (see Figure 2) to design a multiproduct plant that valorises the total textile waste. Before reaching the current conceptual design stage the design procedure has undergone a number of stages; The first involved discrete processing of the different waste textile streams after the mechanical sorting of the main stream. But since the blended material is more abundant than the pure fibre textile wastes the next stage had to combine cascade and discrete processing of the inflow, where cascade refers to the sequential processing of the waste stream and the separation of the products along the production path. In the following three stages several dye removal and product separation steps were included before ending with the final proposition for parallel pure and discrete process configuration (see Figure 3). The evolution of the RESYNTEX process design followed a dynamic iterative workflow between experiments and process design, constrained along the way by feasibility and sustainability targets.

ENERGY AND WATER INTEGRATION

Without any water integration attempts the water consumption is as high as 52 tonnes per tonne of feedstock, and it is shared among reaction and separation stages (mostly washing and filtration steps) at a 2:1 ratio.

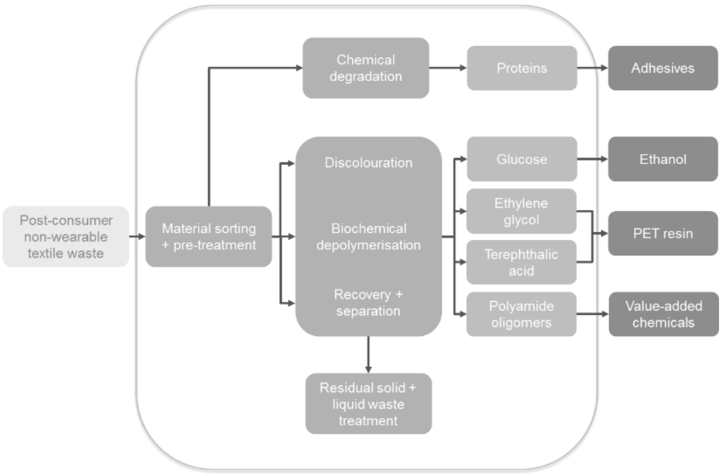

Figure 1 *The RESYNTEX value chains*

Contrary to the textile fabrication processes which uses an average of 30 MJ/kg of fabric [1], TTWR is more energy intensive, requiring more than 53 MJ/kg of feedstock. The majority of the energy requirements (~40%) is used in reactions, which are mainly neutral thermochemical hydrolyses at high temperatures for PAs and PET, and biochemical hydrolyses at mild temperatures. Considering that water is used at high ratios compared to the feedstock material in all reactions, it is also the main energy carrier in the reactors.

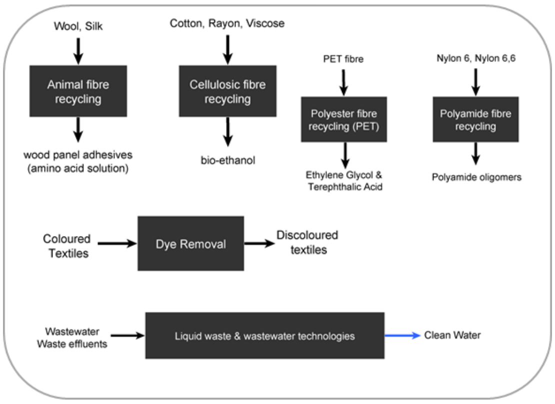

Figure 2 *Individual processes*

This evidence indicates clear scope for a combined energy and water integration study, since water is used both as a cleaning agent for removing dyes and impurities as well as the main heating medium. Novel process integration tools have been developed for assessing alternative process integration scenarios and achieving maximum efficiencies in energy and water use in modern biorefineries [2]. Also, total waste management and recycle design technology has been produced to enable the development of designs for processes with minimum environmental impact [3].

A new tool is proposed in this paper for targeting maximum energy and water efficiencies in the TTWR. It is developed by using a mathematical programming superstructure model which balances the preference towards energy and water saving goals. The application of the proposed tool in the design of the TTWR is able to produce significant energy and water saving targets, that may reach up to 80% for energy and 40% for water.

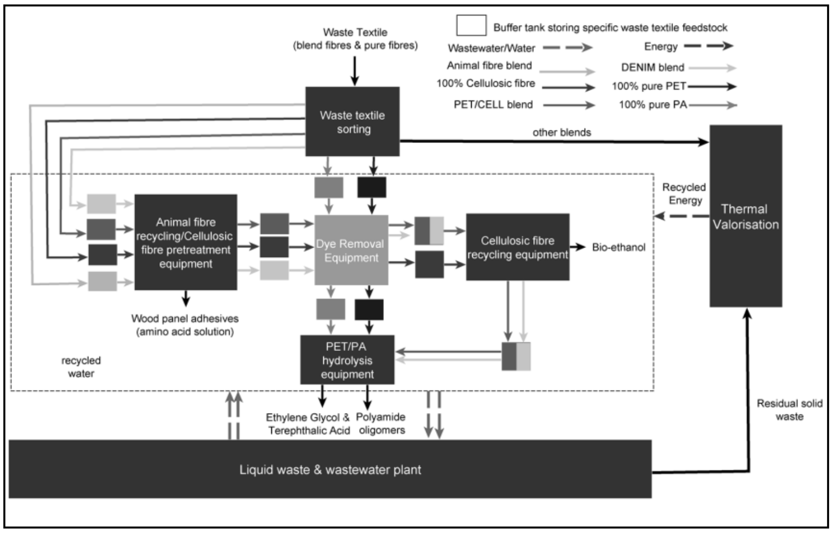

Figure 3 *Current parallel lines RESYNTEX process*

PROCESS EVALUATION

The basis of the cost analysis for the process has been the pilot and pre-pilot process. The economic evaluation resulted in annualized capital cost of €4.67 M, and total annualized cost of €16.36 M for a 100 t/y waste processing capacity plant. The Internal rate of return (IRR) for the investment is -27.97%. Improvements are possible but certainly the scope is not enough to invest on the plant as presented. The analysis of process cost and product prices uncertainties has shown that the current selling prices of products are low and can justify entry to the market only above optimal processing capacity of 2 m t/y combined with the benefits that the learning effect will bring for this innovative process through the proliferation and replication of the technology. Table 1 reports break even prices and optimal processing capacities that must be reached to achieve sustainable production.

STRATEGIES FOR VIABILITY AND INDUSTRIAL SYMBIOSIS

The assessment of the business concept from the higher level of Industrial Symbiosis perspective produces interesting results when considering upstream as well as downstream industrial integration of the textile refinery.

Table 1 *Break even prices and optimal processing capacity for sustainable production*

Product	Positive profit beyond product price	Optimal processing capacity (tn/yr)
All products	Beyond 25%	1,100,000
PTA	Beyond 22.5%	1,000,000
Peptides	It does not make profit even at 200% product price increase	
Glucose	Beyond 120%	1,000,000

Upstream inflows include caustic soda, HCl and water, while downstream integration features cellulose and glucose streams, mergers of TA and PA product streams with virgin production and diverting wastewater to nearby plants.

Industrial integration of upstream flows

Regarding the use of caustic soda, high quality (48% w/w) is mainly used for the PET hydrolysis and to a smaller extend for the hydrolysis of PA[4], while low quality: 52% of caustic is used for extrusion and discoloration. Integrating inter-industrial flows of caustic soda provides for 2.8 M€/year free cash flow. Good quality of sulfuric acid may be preferred over HCl for the neutralization of reaction mixtures (cellulose, denim, cellulose/PET) and product solutions (PET, PA). Given that H2SO4 is 3-4 times less expensive than HCl 50% substitution may result in 1.6 M€ savings per year.
The amount of water consumed is significant adding up to 24 t/h accounting for 13% of the utility costs, and importantly most of it is drinkable water. By using industrial filtered water in more than half of the volume (e.g. discoloration and first washing step after discoloration) the cost is lowered by a factor of 2, resulting in 1.7 M€/year savings.

Industrial integration of downstream flows

Transferring 10% of diluted glucose (e.g. to nearby fermentation plant at 100 km) instead of expensively condensing the syrup results in 1.2 M€/year energy savings, and also in a fixed cost reduction of 5.6 M€ at the expense of additional 1.8 M€ of transport costs. The overall savings amount to 5 M€/y. Another option is to selectively short initially unsuitable cellulosic streams and apply new upgrade technologies to remove impurities such as metals, elastane, other fossil polymeric fibres, dyes, additives and finishing agents detrimental to fermentation, resulting in combined CAPEX and OPEX annualized savings of 8M€/year. The main challenge for marketing the products is the quality standards and the high costs of purification to reach them. The solution proposed for the recycled terephthalic acid (r-TA) challenge is the symbiosis of the process with virgin producers and the production of mixed r-TA with fossil TA. Notably 4 typical PTA plants (350-950 kt/year) can easily absorb 8.5 kt of r-TA per year. As in the case of biofuels, regulation may promote the blended product. For the case of recycled polyamides (r-PA) only small savings, reaching several hundred thousand can be attained by sending r-PA to existing units, since the global production of PAs is only 6.5 Mt/y. Wastewater from several process lines can be used in the manufacturing of phenol-formaldehyde resin and particleboards without loss of properties, albeit with limited scope for savings. Table 2 summarizes the impact of symbiosis and other strategies on the economic viability of the process. It is shown that positive cash flow is possible but still additional incentive is needed to justify the large capital expenditure.

Table 2 *Impact of symbiosis and other strategies on the economic viability of the process*

	Free cash flow (M€/year)	**Improvements of free cash flow vs base case (M€/year)**	**CAPEX for 80 kt/year (M€)**
Base case: 1 x 80 kt/year plant producing 80% glucose juice	-25		207
Decentralized chemical plants (3 x 27 kt/year)		-8	304
New textile feedstock for Resyntex plant 1 x 160 kt/year plant		+6 (for 80 kt)	162 (for 80 kt)
Symbiosis at the door of a 2G ethanol plant		+8	93
Resyntex plant at the door of ethanol or lactic acid plant		+7	104
Better value for glucose juice (2G ethanol or lactic acid)		+4	
Symbiosis with a low-cost caustic soda producer		Up to +2.5	
Partial replacement of hydrochloric acid by sulfuric acid		+1.6	
Partial substitution of demineralized/tap water by industrial filtrated water		+1.7	
Extended producer responsibility fee on new clothes corresponding to 0.1€/kg textile waste to be chemically recycled		+8	

CONCLUSIONS

It is shown that centralized capacity is better but it incurs high investment costs and may restrict opportunities for symbiosis. A more sustainable business concept could be based on higher-value products. Contrary to conventional wisdom, trade-offs balance between decentralized and centralized plants not in comparing logistics vs CAPEX but primarily through the options to explore symbiosis. Upstream and downstream symbiosis is the enabler of a sustainable process by making use of lower purity chemistry upstream (low quality caustic, sulfuric acid, replacing partially hydrochloric acid, use of industrial filtrated water), and linking downstream with 2G ethanol plant or 2G lactic acid plant, also by sharing r-TAs and r-PAs with virgin plants following the paradigm of biofuels/fossil fuel mix. Producer and consumer responsibility play an important role and fee on new clothes could justify investment. Incentive set to 100 €/t of used textile (that is chemically recycled) could turn the investment attractive.

ACKNOWLEDGEMENT

This project has received funding from the *European Union's Horizon 2020 research and innovation program* under grant agreement No 641942.

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