Slutrapport för projekt

Termokemisk återvinning av polymerer

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Termokemisk återvinning av polymerer

Feedstock recycling of polymers

Titel på projektet – svenska Återvinning av polymerer
Titel på projektet – engelska Recycling of polymers
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Preface

”Recycling of Polymers” is an individual (“enskilt”) project financed by RE:Source with the objective of supporting innovations that help to decompose and convert polymer rejects from mechanical recycling into building blocks for new polymers, so-called feedstock recycling methods. The project was conducted in form of three workshops that have attracted participants representing the entire value cycle for polymers, including chemical and petrochemical industry, polymer users/goods manufacturers, consumers and municipalities, recycling industry, research and innovation structures, feedstock recycling companies, industry organizations, etc.

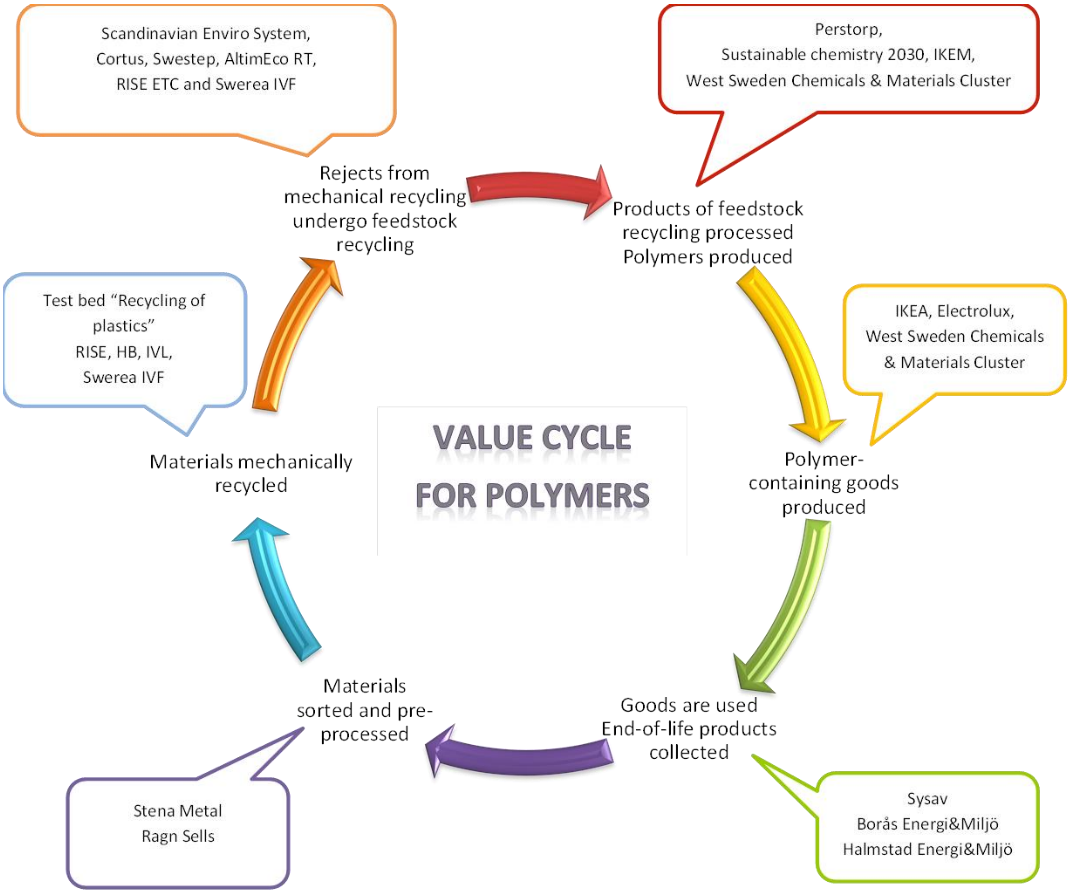

Figure 1 Project participants representing the entire value cycle for polymers

As the building of stakeholders' networks and the analysis of the current state of the innovation system were of major importance to the project, active participation of stakeholders was crucial for the success of the project. More than 25 organizations have been involved in the project directly and more than 1000 are accessible through branch organizations.

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Sammanfattning

Feedstock recycling, dvs nedbrytandet av långa polymerkedjor till dess beståndsdelar och den efterföljande syntesen, är nödvändighet för att möjliggöra hållbara cirkulära flöden av polymera material och framför allt i de fall då mekanisk återvinning är begränsad. Det är viktigt att belysa att feedstock recycling inte bara fungerar för att lösa återvinningsproblematiken av komplexa, kontaminerade och blandade polymerflöden utan behövs även för enklare flöden eftersom polymerer åldras och polymerkedjorna kortas av för varje användarcykel. Detta projekt syftar till att stödja innovationer inom området och specifikt att:

- forma ett nätverk, den så kallade feedstock recycling plattformen, som fungerar som en arena för att underlätta kommunikation mellan olika intressenter och därigenom främja utvecklandet av tekniker och processer
- kartlägga nationella och internationella aktörer, metoder och tillgänglig teknik
- analysera den nuvarande situationen och identifiera hinder och barriärer för en fortsatt marknadsutveckling genom TIS-analys (transition innovation system analysis)
- diskutera möjliga verktyg för att utbilda och hjälpa potentiella användare att hitta lämpliga tekniska lösningar och möjliga samarbetspartners för feedstock recycling
- identifiera åtgärder för att underlätta en lyckad utveckling inom området

Dessa mål har uppnåtts. Det föreslagna nätverket var efterfrågat hos intressenterna och det framkom även som ett viktigt resultat av innovationssystemanalysen.

Avsaknad av legitimitet och en svagt utvecklad marknad framkom som de största hindren för utvecklingen inom området i dagsläget. Följande faktorer identifierades som viktigast för att skapa legitimitet för feedstock recycling:

1. Utbilda intressenter för att skapa acceptans och stödja vidare utveckling
2. Tydliga kriterier för användandet av feedstock recycling och transparens i beslutsfattandet
3. Kompabilitet med existerande infrastruktur inom avfallshanteringen (bidrar till acceptans)
4. Utveckling av koncept för fullskala och demonstration av viktiga tekniklösningar

Formering av en marknad för feedstock recycling i Sverige är i ett tidigt skede och nästa steg i utvecklingen är att skapa en gemensam agenda. Detta följer de steg som är nödvändiga för att formera en marknad. Dessa är:

1. En arena för nätverkande/kommunikation och kreativ interaktion mellan intressenter behövs för att:
    a. formulera en gemensam syn på utvecklingen
    b. skapa en gemensam agenda
    c. hitta en samsyn för rollfördelningen i den nya värdekedjan (vilken typ av aktör ska bygga/äga/använda en feedstock recycling anläggning?)
2. Säkerhetsställa att tillräcklig mängd och kvalitet på materialflödena så att produkten kan produceras med tillräckligt god ekonomi (det kan innebära samarbete mellan olika intressenter för att kombinera mindre materialflöden)

Nästa steg för att förbättra innovationsklimatet inom området är att skapa en formell struktur (långvarig plattform eller komptenscenter) som förenar aktörer och därigenom fyller ett antal funktioner.

- Informationskanal för att sprida kunskap om feedstock recyling till intressenter, myndigheter och allmänheten
- Arena för kommunikation och samarbete mellan intressenter
- Representera feedstock recycling i samhälleliga processer och bidra till en acceptans av dess roll inom polymerers värdekedja
- Att attrahera medel till området för att underlätta innovationer

Att utrusta denna struktur med ett verktyg för utbildning och kommunikation som är tillgängligt för alla intressenter är också viktigt för en vidare utveckling.

Summary

Feedstock recycling is the key for enabling circular flows of polymers in those many cases when mechanical recycling is restricted. It is important to emphasize that feedstock recycling is imperative not only for solving recycling problem for complex, contaminated or mixed polymer streams but rather for all polymer materials in general since all polymers are subject to aging and after certain service time/recycling cycles become reject from mechanical recycling. This project was aimed at supporting innovations in this area, in particular:

- at creating a network, the so-called Feedstock Recycling platform, that would serve as an arena for interaction between stakeholders reducing communication lines and promoting innovative processes in the area,
- at organizing information on current development including national and main international actors, methods, available equipment and best practices,
- at analyzing the current situation and identifying obstacles and barriers for further market development using relevant methods, e.g. the Transition Innovation System (TIS) analysis,
- at discussing possible instruments to educate and assist potential users in finding suitable feedstock recycling solutions and partners for their projects,
- at identifying actions to be undertaken to ensure future successful development of this innovation area.

These objectives have been achieved successfully. The offered networking opportunities proved to be demanded by stakeholders. The ultimate importance of networking was also pointed out by the results of the performed analysis of the innovation system.

Lack of legitimacy and underdeveloped market has been named the most pressing problems that hinder development at the moment. The following factors were identified as the most important for creating legitimacy for feedstock recycling:

1. Educating stakeholders for creating acceptance and supporting further development.
2. Clear criteria for using feedstock recycling methods and transparency in the decision making.
3. Compatibility with the existing waste management infrastructure (contributes to acceptance).
4. Development of concepts for a full-scale process together with demonstration of key technical solutions.

Formation of the market for feedstock recycling in Sweden is at rather initial stage, and creating a common agenda seems to be the nearest target on the way. The following necessary steps for market formation have been named:

1. An arena for networking/active communication/creative interaction between stakeholders is needed in order to
    a. develop a common view on the development,
    b. create a common agenda, and
    c. agree on the role distribution in the new value cycle (who should build/run/own a feedstock recycling facility?).
2. Finding sufficient material flows for achieving good economy is important (possibly also through cooperation between stakeholders by combining smaller material streams).

The next step in improving the innovation environment in the area should be to create a formal structure (a platform or a competence center) that unites actors and is suitable for the following functions:

- act as a channel to disseminate knowledge on feedstock recycling among stakeholders, authorities and the public,
- serve as an arena for communication and collaboration between stakeholders,
- represent feedstock recycling in societal processes and contribute to the common acceptance of its role in the polymers' value cycle,
- attract funds to enable innovations (in later stages).

Equipping this structure with an educational and communicative instrument available to all stakeholders would be of additional value for further development.

Introduction and background

Feedstock recycling is the key for enabling circular flows of polymers in those many cases when mechanical recycling is restricted. It is important to emphasize that feedstock recycling is imperative not only for solving recycling problem for complex, contaminated or mixed polymer streams but rather for all polymer materials in general, see Figure 2. This is due to the fact that all polymers are subject to aging and cannot, consequently, be reused or material recycled endlessly. After certain service time/recycling cycles all polymers become reject from mechanical recycling and need to be broken down into basic hydrocarbon units or constituent monomers in order to be effectively reused again as raw materials in chemical or petrochemical processes.

Figure 2 Feedstock recycling methods convert rejects from mechanical recycling into building blocks for new polymers

Today's society is driven by a philosophy of circular economy and zero waste. The concept, in which today's goods become tomorrow's resources, seems to be the only reasonable line of development for humanity in a world of finite resources. Plastics and polymers presently stand serious challenge for this concept. These materials serve numerous applications of critical importance to society while being one of the most pervasive environmental problems. Approximately 8.3 bn tons of plastic have been produced to date, of these approximately 6.3 bn tons have become plastic waste[1]. Even with increasing recycling rates in the EU, only 30% of plastics are

[1] http://www.bbc.com/news/science-environment-42264788

currently recycled, i.e. preserved in a cycle[2]. All this makes the successful development of efficient feedstock recycling technologies highly demanded. Current project is aimed at supporting innovations in this area.

A few feedstock recycling methods with the large number of modifications and innovations around them have been developed over the last 30-35 years. However, these methods have still not found wide industrial application due to a number of reasons, such as weak legislative stimulation of recycling and the instability of prices for virgin raw materials. This situation is further complicated by obstructed communication between stakeholders in the fragmented and underdeveloped market. Potential user and the supplier of an appropriate technology have difficulties in finding each other. Sources of reliable information about the possibilities, limitations and current development of various methods are either absent or difficult to access.

This project has been aimed at addressing these communicative problems:

- at creating a network, the so-called Feedstock Recycling platform, that would serve as an arena for interaction between stakeholders reducing communication lines and promoting innovative processes in the area,
- at organizing information on current development including national and main international actors, methods, available equipment and best practices,
- at analyzing the current situation and identifying obstacles and barriers for further market development using relevant methods, e.g. the Transition Innovation System (TIS) analysis,
- at discussing possible instruments to educate and assist potential users in finding suitable feedstock recycling solutions and partners for their projects.
- at identifying actions to be undertaken to ensure future successful development of this innovation area.

Implementation

The project has been carried out in the form of three workshops, a number of individual interviews and smaller meetings conducted over 15 months' time. The project was initially scheduled for 12 months, 3 months extension was needed mainly due to the involvement of a large number of participants, which required longer notice times for finding suitable dates for the workshops. HB has acted as project coordinator. HB and RISE made main contribution to the project management, preparation and processing of workshop materials, with minor contribution from Chalmers and KTH.

WS1

The first workshop was conducted on May 4th, 2017 in Gothenburg. The entire value cycle for polymers has been represented, including:

[2] http://ec.europa.eu/environment/waste/pdf/pan-european-factsheet.pdf

- **Chemical and petrochemical Industry** represented by Perstorp, Sustainable chemistry 2030/Chemical companies in Stenungsund and West Sweden Chemicals & Materials Cluster;
- **Polymer users/goods manufacturers** represented by IKEA and West Sweden Chemicals & Materials;
- **Consumers and municipalities** represented by Sysav, Borås Energi och Miljö and Halmstad Energi och Miljö;
- **Recycling industry** represented by Stena Metal and Ragn Sells;
- **Research and Innovation structures** working with/dedicated to recycling of plastics and polymers represented by the Test bed for recycling of plastics, HB, RISE and Swerea IVF;
- **Feedstock recycling companies** - Cortus, Scandinavian Enviro Systems, Swestep and **research structures** working with/piloting feedstock recycling methods – RISE/RISE ETC, HB and Swerea IVF.

Expectations of stakeholders

The construction of the Feedstock Recycling Platform as an independent forum for all stakeholders in the polymer value chain has been welcomed by all stakeholder groups. Stakeholders' expectations from the participation in this forum are summarized in Figure 3 below.

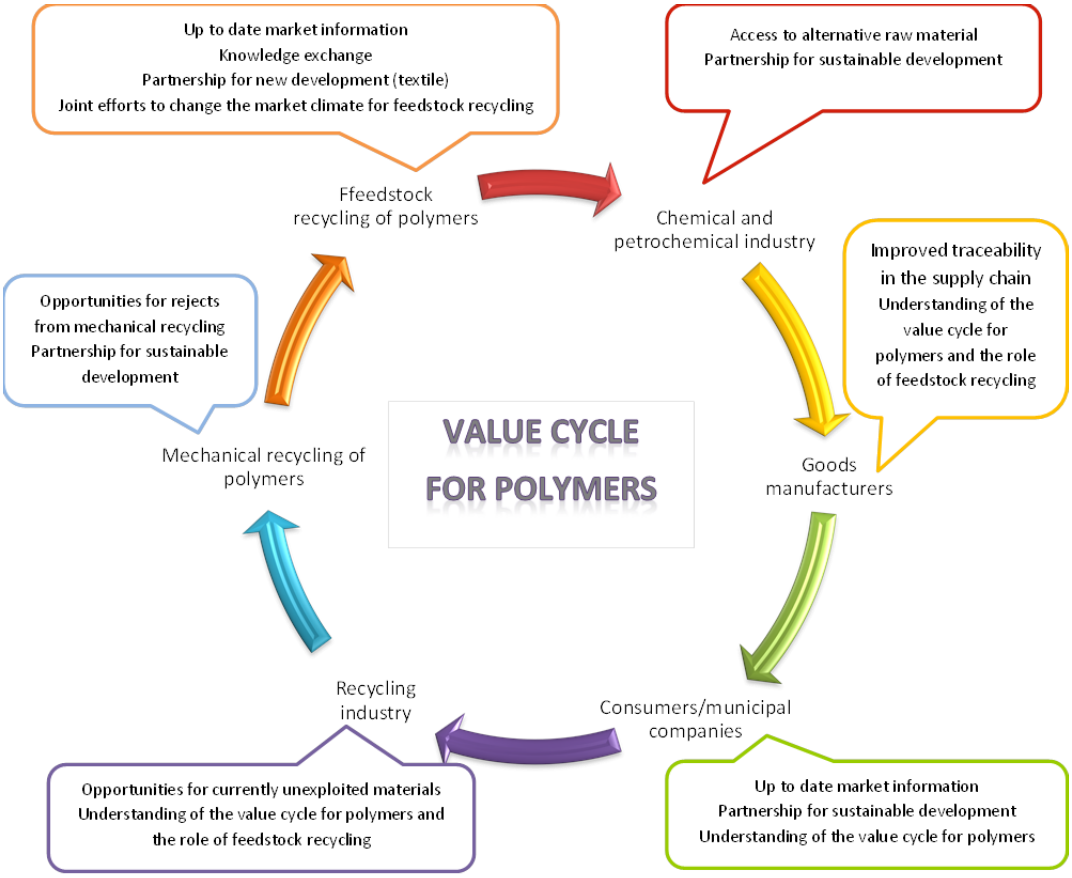

Figure 3 Stakeholders' expectations related to the construction of the Feedstock Recycling Platform

The basis for risk analysis

One of the assignments at the workshop was a brainstorming session, during which pro and counter arguments for successful market development of feedstock recycling have been listed.

The following drivers and obstacles to the development of feedstock recycling have been stated:

Driving forces for the development of feedstock recycling

- Offers effective method for separation of organic and non-organic materials
- Provides recovery solution for durable plastics
- Offers solution for current rejects from other types of recycling
- Preserves materials in the production cycle, which fit the current strong tendency to circular development
- Provides a source of alternative raw materials with lower carbon footprint

- The development in Sweden can be facilitated thanks to existing skills and motivation

Obstacles for the development of feedstock recycling

- High investments needed
- Difficult to economically compete with incineration
- Technical problems - sorting, feeding, halogen, restricted chemicals, etc.
- Low price for virgin raw materials
- Missing infrastructure /logistics/etc.
- Too small output material flow/not enough to substitute virgin materials, which leads to lower interest in the development
- The quality of the products differs from the quality of virgin raw materials
- Historically formed bad image (unsuccessful investments)
- Unclear environmental performance - risk to act against sustainability
- Lobbing against feedstock recycling from oil industry, etc.
- Lack of political support, e.g. difficult to obtain environmental permits
- Skewed public perception of plastics - plastics will become obsolete
- Lack of wiliness to invest due to high investments needed and high risks

Technology offer and customer requirements

General overview of technical solutions available on the market and under development, prepared by the project management group, has been presented and discussed with the workshop participants (see the Results and Discussion section of current report).

Current technical development and available equipment have been presented by Swedish technology providers and research institutions (see the Results and Discussion section of current report).

Customer requirements and concerns regarding feedstock recycling of polymers have been discussed with different stakeholders groups.

IKEA

IKEA is interested in improving traceability and sustainability. Secondary raw materials are of interest provided that:

- materials and products comply with IKEA specifications (e.g. no heavymetals,no Cl, etc),with food contact specifications, and with childrensproducts specifications,
- the price is affordable for the many.

Mainly PP and PET materials are of interest.

IKEA wants to get a clear understanding of the possible closed loop for plastics. The linear model today consists of production (refinery), granular supplier, national company supplier, store costumer and disposal. Some specific questioned raised were:

- Where is the pyrolysis/feedstock recycling place in the diagram? Does it substitute the refinery or even the plant for granulate production?
- Where should the feedstock recycling plant be located – close to a waste sorting facility or close to a granulate producer?
- What are the minimum/optimal volumes that can make feedstock recycling products competitive?
- How to set up disposal schemes in all countries where IKEA is present?
- What systems for the separation of materials suitable for mechanical recovery from the material to be feedstock-recycled are currently available? What information on volumes of fractions is available?
- What will be the costs associated with the transition to such closed-loop scheme?

PERSTORP

Feedstock recycling products that are of interest:

- syngas from gasification,
- isomers from the depolymerisation process,
- products of methanolysis or hydrolysis,
- benzene, toluene and xylene from pyrolysis.

MUNICIPAL COMPANIES

Interest of municipal companies to feedstock recycling is driven by their desire to reduce the environmental impact and to facilitate the transition to the circular models.

Important requirements to the system to be created – economy, availability, easy to use. Quality of the feedstock recycling products currently anticipated by municipal companies is “the same as virgin”.

Acceptance by the end user is of high importance. More end user representatives should be involved in the Platform.

WS2

The second workshop was held on September 21st, 2017 in Stockholm.

Participants of the workshop:

- **Chemical and petrochemical Industry** represented by IKEM, Perstorp, Sustainable chemistry 2030/Chemical companies in Stenungsund and West Sweden Chemicals & Materials Cluster;
- **Polymer users/goods manufacturers** represented by IKEM, Electrolux and West Sweden Chemicals & Materials Cluster;
- **Consumers and municipalities** represented by Borås Energi och Miljö;
- **Recycling industry** represented by Stena Metall and Ragn-Sells;
- **Research and Innovation structures working with/dedicated to recycling of plastics and polymers** represented by KTH, Chalmers, RISE and IVL;
- **Feedstock recycling companies -** Cortus, AltimEco recycling Technologies, Swestep
- **Research structures** working with/piloting feedstock recycling methods – RISE/RISE ETC and KTH.

Assisting the decision making

The topic of WS2 was the development of the methodology for finding technically feasible and economically viable solutions for different polymer streams based on their structure and properties. The methodology is to serve as the basis for an instrument that will educate potential users and help them in decision making.

A suggestion for guidelines to the technology selection process prepared by the project management team has been presented and discussed with the workshop participants (see the Results and Discussion section of current report). The suggested selection process has been tested in two "express case studies". Two materials were included for the discussion:

1. ProFuel from Stena Recycling

This fuel originates from recycling of cars together with scrap from municipality and other activities and consists mainly of metals, rubber, textile and mixed plastics. It is the residue from the shredder light fraction after iron, metal and plastic removal.

Quantity around 20,000 tons/year in Sweden

Heating value 15-20 MJ/kg

Moisture 2-5 %

Ash approx. 30-35 %

Chlorine <0.8 %

2. Paper-reject from Smurfit Kappa

The paper-reject comes from the recycled-paper mill and consists of rejects from the production. These could be different plastic adhesives such as tape, plastic pieces from envelopes and short cellulose fibres. Moisture ca 40 % before drying

Moisture	**% w/w, dried**	**1.0**
Volatiles	% w/w, dry	76.5
Ash	% w/w, dry	21.0
C	% w/w, dry	52.9
H	% w/w, dry	7.5
N	% w/w, dry	0.49
O	% w/w, dry	16.6
S	% w/w, dry	0.138
Cl	% w/w, dry	1.34
H/C_{eff}		1.193
LHV	MJ/kg, ds	24.294
HHV	MJ/kg, ds	25.898
HHV	MJ/kg, ds, ash free	30.752
Si	mg/kg, ds	20 661
Al	mg/kg, ds	8 997
Ca	mg/kg, ds	36 664
Cu	mg/kg, ds	1 890
Fe	mg/kg, ds	13 300
K	*mg/kg, ds*	*971*
Mg	mg/kg, ds	1 966
Mn	mg/kg, ds	264

Na	*mg/kg, ds*	*3 643*
P	mg/kg, ds	349
Ti	mg/kg, ds	1817
Zn	mg/kg, ds	1900

Following comments and suggestions that occurred in the discussion can be listed:

PROFUEL FROM STENA RECYCLING

Fixed-bed gasification and pyrolysis have been discussed as possible methods for recycling where the latter is likely to provide better results due to the high amount of ashes contained in the pelleted waste.

The material is not suitable for e.g. the Cortus process due to high content of volatiles and high ash content.

PAPER-REJECT FROM SMURFIT KAPPA

Pyrolysis can be suggested as a promising alternative for processing.

Pre-treatment in form of drying/grinding/dechlorination at ca 300 ° C is required.

Pyrolysis at approximately 500 ° C temperature will help to ensure sufficient demineralization and low ash content in the pyrolysis oil.

This material is not suitable for e.g. the Swestep process that can accept max 15% moisture, max 5% inert contaminants and max 5 mm large particles.

GENERAL COMMENTS FROM WORKSHOP PARTICIPANTS

The decision-making tool that has been discussed at the workshop should not be made too detailed and complicated as it can easily become misleading. It should be made very clear that the tool is not to give economic evaluation but only technical suggestions and some input (resource-efficiency, sustainability) for further selection of processing methods. The tool is anticipated to have a good potential for making feedstock recycling projects more economically viable through e.g. combining flows and creating a market place for products.

Obtaining renewable ethylene and methanol from products and materials that society wants to get rid of (and is prepared to pay for) has been indicated as the highest interest for the chemical cluster in Stenungsund. Obtaining these chemicals from waste can lead to a better economy compared to, for example, producing methanol from biomass (forest materials), as in this way transport of methanol can be avoided.

A general comment received from all discussion groups was the importance of correct and essential information in the material description. For thermochemical processes this includes (but is not limited to): moisture content, ash content, chemical composition, heating value and amount of fixed carbon.

Future steps in the project

In addition to the main workshop topic future steps in the project have been discussed at the WS2. In particular, why and how TIS analysis will be used at the WS3, potential involvement of authorities and decision makers in the WS3, and possible examples of the most successful feedstock recycling companies have been discussed. A few smaller meetings with stakeholders have been scheduled.

WS3

The third workshop was held on February 28th, 2018 in Gothenburg.

12 participants including representatives of Perstorp, IKEA, RagnSells, Scandinavian Enviro Systems and ART could not get to the workshop due to stormy weather in Sweden that day. However, representatives from different stakeholder groups participated in the workshop:

- **Chemical and petrochemical Industry** represented by IKEM, Sustainable chemistry 2030/Chemical companies in Stenungsund and West Sweden Chemicals & Materials Cluster;
- **Polymer users/goods manufacturers** represented by IKEM and West Sweden Chemicals & Materials Cluster;
- **Consumers and municipalities** represented by Borås Energi och Miljö, SYSAV and RENOVA;
- **Recycling industry** represented by Stena Metal;
- **Research and Innovation structures working with/dedicated to recycling of plastics and polymers** represented by HB, RISE and IVL;
- **Feedstock recycling companies -** Cortus, Swestep
- **Research structures** working with/piloting feedstock recycling methods – RISE/RISE ETC.

TIS analysis

The network/platform that the project aims to build will become a part of the innovation system for feedstock recycling. One way to analyse the needs that the platform should serve is to analyse the innovation system. Based on the results of such analysis, the prerequisites for establishing the platform can be found and the role of the platform in the development of innovations can be detected.

A system approach that is often used to identify obstacles and opportunities for the development and dissemination of innovations is TIS. The TIS framework consists of a two-part analysis of the innovation system structure and the innovation processes, see Figure 4 below.

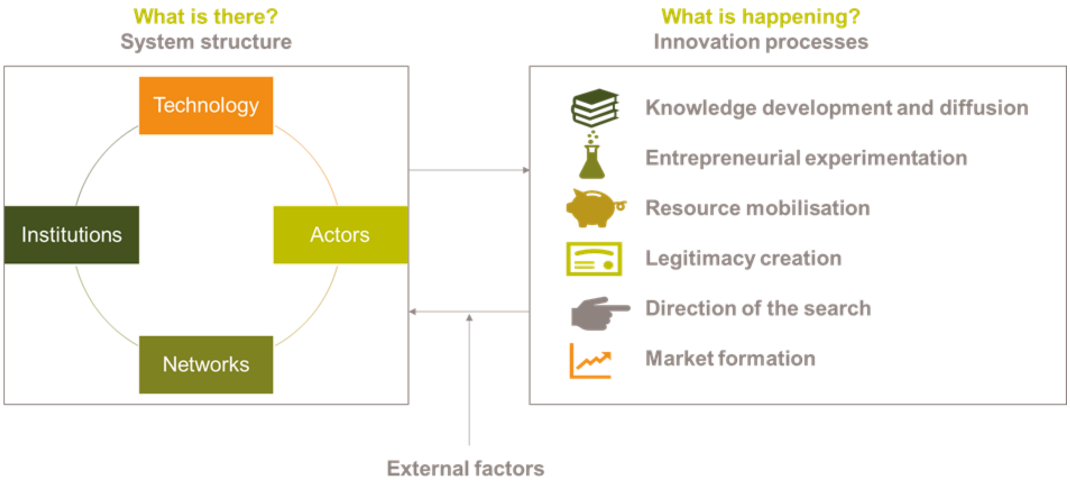

Figure 4 Two parts in the analysis - structure of the innovation system and innovation processes

Structure analysis - to understand the relationships between the technology, stakeholders, networks and institutions. This part helps to identify the status of the development as well as factors limiting the development of the system.

Innovation Process Analysis - to analyze innovation processes driven by stakeholders/players inside and outside the system. How strong or weak the processes are gives a picture of how successful the development of the system is.

As a result, existing barriers and actions that have to be undertaken in order to move forward in the innovation process can be identified.

Extensive preparations with the participation of the project management team and stakeholders have been carried out before the workshop to compile relevant questions to the participants. Initial questions have been sent and opinions collected from the participants. 3 physical meetings and a number of online meetings have been conducted.

The first part of the workshop was intended to identify the feedstock recycling (FR) system elements with the active assistance of the participants and based on the results from the two previous workshops. During the second part of the workshop, analysis of innovation processes has been carried out using guided group discussions. Two innovation processes chosen by participants as issues of primary importance have been discussed, namely, market formation and creation of legitimacy. Resource mobilization and entrepreneurial experimentation were, however, also named as matters of great interest.

Other processes/functions were analysed with help of a post-workshop survey sent to all participants of the platform. The results of the performed analysis are presented in the Results and Discussion section of current report.

Future of the platform and more information on best practices

Different models for future development of the platform and the results of the additional study on best feedstock recycling practices performed by the project management team have been presented at the WS3. Information obtained in the interviews with the senior management of the Canadian company Enerkem (see the Results and Discussion section for more information) raised the greatest interest among stakeholders. What Enerkem see as the most important factors for success, how the legislation affects their business, which are the main directions for future development and the Enerkem project planned in the Netherlands – these were the main topics of stakeholder discussion.

Results and discussion

Overview of the feedstock recycling methods

What is feedstock recycling of polymers?

Feedstock recycling, also known as thermochemical or chemical recycling, covers a range of processes by which polymers can be broken down into basic hydrocarbon units or constituent monomers that can then be used again as raw materials in chemical or petrochemical processes. A range of technologies with the large number of modifications and innovations around them is available.

PYROLYSIS

Pyrolysis is chemical decomposition of organic (carbon-based) materials at elevated temperature and in the absence of air or oxygen, with the formation of syngas and liquid hydrocarbons as products. A mixture of un-reacted carbon char (the non-volatile components) and ash remains as a residue. The temperature range usually used for pyrolysis is 200-800°C. As non-oxidizing environment is essential for pyrolysis, the process is quite sensitive to moisture present in the material to be processed.

Problems that the development of pyrolysis has traditionally faced is the dubious quality of the products obtained by conventional high temperature pyrolysis and hazardous compounds formed in conventional processes, especially when waste plastics contain chlorine, bromine and various metallic impurities.

The latest generation of pyrolysis technologies uses different catalysts and dechlorination methods to lower process temperatures, improve product quality and mitigate emission problems[3,4]. These new methods aim to accept a variety of resin types, tolerate many forms of contamination and require little pretreatment. Also, rectors of various designs, which have their advantages and disadvantages in different cases, are used in various modifications of pyrolysis[5,6].

[3] http://www.ijaet.org/media/12I29-IJAET0829561-v8-iss5-794-802.pdf
[4] https://www.sciencedirect.com/science/article/pii/S0926337311001433
[5] https://www.researchgate.net/figure/Types-of-pyrolysis-reactors_fig1_287506521
[6] http://shodhganga.inflibnet.ac.in/bitstream/10603/10119/12/12_chapter5.pdf

GASIFICATION

Gasification occurs in a higher temperature range than pyrolysis (often 480-1,650°C but even higher temperatures can be seen if plasma gasification is used). Gasification is most simply understood as incomplete and carefully controlled staged combustion that uses limited oxygen to convert a carbon-containing feedstock into a synthetic gas (syngas), a mixture consisting primarily of hydrogen and carbon monoxide. This syngas can be used as a starting point to manufacture fertilizers, pure hydrogen, methane or other high-value chemicals including anhydrous ammonia, ammonium sulfate, sulfur, phenol, naphtha and CO_2, as well as liquid transportation fuels. Carbon char present as residue in the pyrolysis process is converted in the gasifier into syngas. Only ashes remain as a residue.

Gasification of waste polymers has reached a higher TRL than pyrolysis and is even used on a large industrial scale, for example by Enerkem, Canada. This is probably due to the product with simpler compositions and versatile use, and less complicated control of process parameters with regard to their impact on product quality. A large variety of process modifications and different types of reactors are currently used[7,8]. For more details and a list of recent feedstock recycling projects please see Appendix 1.

HYDROTHERMAL LIQUEFACTION (HTL)

HTL converts carbon-containing materials into liquid hydrocarbons by breaking down their organic structure in the presence of solvents and /or catalysts and at elevated temperature /pressure. HTL is carried at temperatures in the range of 250–450 °C, and pressures in the range of 5–20 MPa. HTL is an attractive low temperature option for very moist raw materials and when liquid products are desired. Interest in this method for processing waste plastics is growing and new research has recently been published[9]. Current status of this technology is on the developing stage with several actors utilizing laboratory sized equipment.

CHEMICAL DEPOLYMERIZATION

Certain classes of polymers like polyesters , nylon or lignin can undergo chemolysis with different reagents, such as water (hydrolysis), alcohols (alcoholysis), acids (acidolysis), glycols (glycolysis), and amines (aminolysis) to produce the monomers from which they have been produced or other oligomers. Different process options are used industrially for chemical recycling of PET - methanolysis for production of dimethyl terephthalate (DMT) and ethylene glycol (EG), hydrolysis for production of pure Terephthalic acid (TPA) and EG, conversion into oligomers (glycolysis or solvolysis), conversion into speciality chemicals by aminolysis or ammonolysis, etc. Application of chemical depolymerization for recycling of mixed materials, such as

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[7] https://en.wikipedia.org/wiki/Gasification
[8] https://www.netl.doe.gov/research/coal/energy-systems/gasification/gasifipedia/types-gasifiers
[9] T. Helmer Pedersen and F. Conti, "Improving the circular economy via hydrothermal processing of high-density waste plastics," Waste Management, vol. 68, pp. 24-31, 2017/10/01/ 2017

polyester/cotton blended fabric, are being actively studied[10,11]. The polyester is depolymerised into monomers and the monomers are reused as building blocks for new polyester synthesis, see Figure 5. Besides, the obtained monomers can also be used as chemicals for other applications.

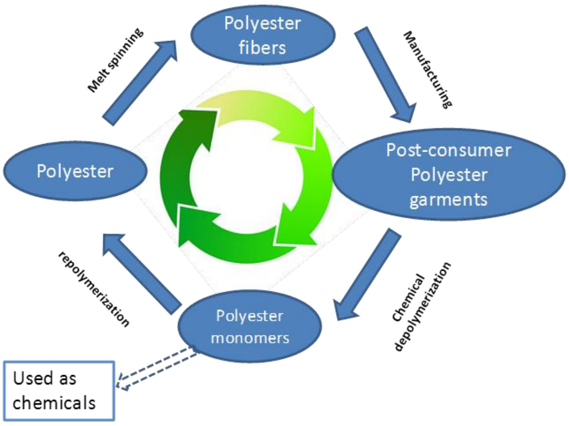

Figure 5 Closed-loop recycling of polyester

Technology development in Sweden

In this section, technology developers in Sweden with processes suitable for feedstock recycling that currently have demonstration/commercial plants are described.

SCANDINAVIAN ENVIRO SYSTEMS

The process – thermal treatment in an oxygen-free environment, fixed bed pyrolysis.

Main advantages – good temperature control, stable temperature through the reactor, variety of solid polymer-based materials can be processed (different types and sizes).

Main process limitation – temperature < 650°C

Suitable feedstock – the process has been developed for waste rubber but any solid polymer-based feedstock, e.g. plastics mixtures of complex character, can be processed.

Equipment available – full-scale reactor of 15 m^3

Typical products from the end-of-life tyres – high quality carbon black, oil and steel. All produced material streams are sold commercially.

CORTUS

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10 Trash2Cash, EU project, www.trash2cashproject.eu

11 Anna Peterson, Towards Recycling of Textile Fibers, Chalmers, 2015

The WoodRoll® technology – a fully integrated biomass gasification process. WoodRoll® is based on combining the three processes: drying, pyrolysis and steam gasification.

Main advantages – clean gas is produced, suitable for variety of applications.

Typical feedstock – wood chips, bark, fibre sludge. Potentially a mixture of plastics, paper and wood can be processed. Mixing can be necessary to promote char formation during the pyrolysis stage.

Typical product – syngas with 60 % H_2, 30 % CO, 8 % CO_2, 2 % CH_4, heating value 11 MJ/Nm^3

Cortus has a 500 kW gasification test facility in Köping where a number of different lignocellulose-based materials have been tested. The plant can work in both continuous and batch mode depending on the needs of a project.

Laboratory scale testing is required for each new potential raw material to be approved for testing in the test facility (see the 3-stage testing program suggested by Cortus in Appendix 2). The facility may need to be adapted to run with a new raw material, which may affect installation costs.

A clean plastic fraction is not suitable for treatment in the WoodRoll® facility at existing installation because the process requires a certain ratio between the char-coal and the pyrolysis gas generated in the process. Mixing plastics with biomass, i.e. bark and/or using RFD can be considered as potentially viable solutions.

SWESTEP

The process – Pressureless Chemical Catalytic Depolymerization Process. The process is “a copy of the natural process of converting organic matter into oil accelerated to 3 minutes” thanks to the catalyst and the elevated process temperature (240 – 270 °C).

Main advantages – a storable pyrolysis oil is produced, all hydrocarbon-based organic materials can be processed, scalable plants, efficient conversion (ca 85 %), clean process due to the low temperature used.

Suitable feedstock – all hydrocarbon-based materials including wood, plant residues, energy plants and organic waste, waste plastics, waste oil, etc. Maximum 5% inert material can be accepted.

Equipment available – test plant in Germany (a full scale industrial production line dedicated for tests).

Typical products – “green” bitumen and synthetic oil.

Best practices worldwide

Large number of projects developing feedstock recycling applications for processing waste polymers is ongoing. The most notable of them are listed in the Appendix 1.

The Canadian company Enerkem[12] can be named as a clear leader in the industrial use of feedstock recycling for material recovery from waste (including waste polymers) today.

Enerkem Alberta Biofuels is the world's first commercial biorefinery to use non-recyclable municipal solid waste to produce methanol and ethanol. This facility is the result of more than 10 years of efforts to scale up Enerkem's technology from pilot and demonstration, to full commercial scale. A set of interviews with the company management has been conducted within the framework of the project. According to Enerkem the main success factors for the company are:

- complete compatibility with the existing waste infrastructure,
- banned landfilling and incineration,
- biofuel incentives,
- complete cycle down to marketable products,
- close collaboration with municipalities.

The gasification technique is used to transform the raw material into syngas, which is then converted into biofuels and renewable chemicals. The production of biofuels and the use of residual biomass are dictated by economic necessity. In order to benefit from biofuel incentives, more than 50% of the processed carbon should be of biogenic origin and fuel must be produced. Current legislation in Canada does not reward recovery of non-biogenic carbon from waste or production of secondary chemicals instead of fuel. The conditions are even more difficult in the EU where 100% (compared with 50% in Canada) of carbon in biofuels must have biogenic origin. This will affect the economy of the project currently being developed by Enerkem, Air Liquide, AkzoNobel Specialty Chemicals, and the Port of Rotterdam where Enerkem to lead consortium to develop waste to chemical project in Rotterdam[13].

The scale of the planned project is quite significant. The initial investments, which cover detailed engineering, the establishment of a joint venture and completing the permitting process, will be worth €9 million. The consortium aims to take the final investment decision (FID) for the estimated €200-million project later in 2018. The facility will convert up to 360,000 tons of waste into 220,000 tons (270 million liters) of 'green' methanol. As an equivalent, this was said to represent the total annual waste of more than 700,000 households and represents a CO_2 emission savings of about 300,000 tons. Realization of the project is supported by the Dutch Ministry of Economic Affairs & Climate policy, which have agreed to develop mechanisms and regulation that will help bring this new technology to full scale. Namely, intensifying production of chemicals from secondary resources has been discussed[14]. This may indicate that a feedstock recycling project must be large enough to get all possible

[12] https://enerkem.com/
[13] Waste Management World 16.02.2018
[14] Personal communication with Alex Miles, Director, Commercial Development, Europe, Enerkem

support including legislative to achieve a good economy under current market conditions.

Current development state – results of TIS analysis

The method of TIS analysis was used to identify obstacles to the development of innovations in feedstock recycling, as well as the actions that have to be undertaken in order to move forward in the innovation process.

Conducted in the form of a workshop followed by an online survey, the analysis contained two parts: analysis of the structure of the innovation system and analysis of innovation processes see Figure 4.

Structural analysis helps to identify the status of the development of different system elements as well as factors limiting the development of the system. The results of the analysis are summarized in the Figure 6 below.

Technology

- Matchmaking between material characteristics and suitable technological solutions clearly visualized for users is needed.
- Circular approach should be applied. Enabling multiple cycles in the material use must be prioritised.

Institutions

- Fossil free/biogenic/renewable carbon is highly prioritized over recycled, which is clearly reflected in the legislation and regulation. This does not serve the purpose of increasing resource efficiency. LCA analysis shows that material recyclability and increased service life are the most important factors for increased resource efficiency in materials use. This criterion is by far superior to the origin of the material in terms of its impact on resource efficiency.

Actors

- Chemical and petrochemical industry must be encouraged to use secondary raw materials - products of feedstock recycling. Creating awareness on environmental benefits and technical abilities of the available technologies, and on successful examples of industrial implementation of feedstock recycling are seen as an effective way of doing this.
- Authorities must engage in the dialogue and the development of the FR system.
- Regional support is of high importance.

Networks

- Lack of collaboration has been identified.
- A network of stakeholders across the entire value chain needs to be created.

Figure 6 Analysis of components of the innovation system

Analysis of innovation processes helps to indicate how strong or weak different processes are and provide a picture of how they need to be supported for successful system development.

Lack of legitimacy and underdeveloped market has been named the most pressing problems that hinder development at the moment. The following factors were identified as the most important for creating legitimacy for feedstock recycling:

1. The recycling industry is doubtful about feedstock recycling. This is often caused by insufficient knowledge about environmental and technical performance of feedstock recycling methods, quality of the products and level of the development for different methods. **Educating stakeholders is of primary importance** for creating acceptance and supporting further development.
2. Clear **criteria for using feedstock recycling** methods and transparency in the decision making is important to create acceptance among stakeholders.

3. **Compatibility with the existing waste management** infrastructure contributes to acceptance.
4. **Large scale demonstrations are needed** to legitimize technical solutions.

Unavoidable steps in the transition process accompanying market formation can be visualized as a staircase in the Figure 7 below.

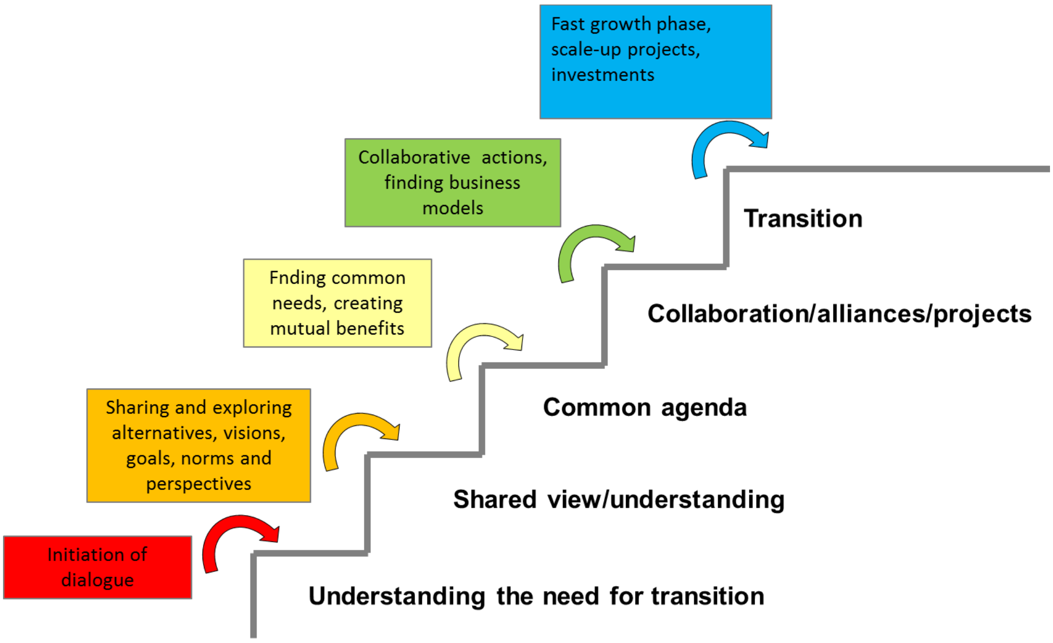

Figure 7 Communicative processes supporting market formation

Formation of the market for feedstock recycling in Sweden is at rather initial stage, and creating a common agenda seems to be the nearest target on the way. It is therefore understandable that the following key factors for market formation have been named:

3. **An arena for networking/active communication/creative interaction between stakeholders** is needed in order to
    a. develop a common view on the development,
    b. create a common agenda, and
    c. agree on the role distribution in the new value cycle (who should build/run/own a feedstock recycling facility?).
4. Finding sufficient material flows for achieving good economy (possibly also through cooperation between stakeholders by combining smaller material streams).

Creating favorable conditions and encouraging entrepreneurial experimentation is of primary importance for successful technical development in the area. Experimentation processes today seem to be hindered by protectionism, significant financial barriers (big investment needed) and a lack of risk distribution mechanisms.

Establishment of a **platform or center that would improve innovation environment** and help to facilitate entrepreneurial experimentation could provide a significant breakthrough in the development. The platform/center in question should

- fit for attracting substantial financing,
- offer equal possibilities for the development of different demand-driven sustainable innovations in the area, and
- attract participants from different stakeholder groups.

Knowledge development and diffusion is closely connected with the process of creating legitimacy that has already been discussed above. According to stakeholders the obvious lack of knowledge about environmental and technical performance of feedstock recycling methods and their role in creating materials cycles is closely related to the fact that the discussion on this topic has only recently started in Sweden, largely thanks to the current project. **Educating stakeholders and the public and creating a clear channel for dissemination of knowledge** are thus actions of high importance for further development.

Another important action that should be taken in order to support the transition processes is to **agree about the role of feedstock recycling in the polymers' lifecycle**. Clear definition of the feedstock recycling place in the polymers' value cycle will serve education and legitimation purposes, encourage resource mobilization and stronger policy support. Finding such a clear and commonly accepted definition is a natural part of a wider discussion on transition to circular models in materials use currently ongoing in the society. An important role of the future network, platform or center is to be a “voice of feedstock recycling” in this discussion.

Assisting the decision making

Discussion on the methodology for matching material flows with suitable technical solutions has shown that the technology selection process can help the potential user to gain a better understanding of the technical possibilities and limitations that the composition of the material entails.

The methodology is to serve as the basis for an instrument that helps the potential technology users in taking their decisions. The instrument also has great educational potential. By using such an instrument, users can not only find potential technical solutions for their needs but also understand current constraints related to structural properties and possible contaminants contained in the material to be processed, as well as the characteristics of different technical solutions.

The process of finding a solution can be divided into three steps: (i) finding technically possible solutions, (ii) selecting the most resource-efficient/most sustainable solutions, (iii) evaluating the economic sustainability of the chosen solutions (finding limits for making them economically viable).

Finding technically possible solutions

To find technically possible solutions following information to be collected:

- Type of material - thermoplastics or thermosets?
  This information is usually available and can be of use as it indicates the amount of solid residue potentially formed when heated. Based on this information, for example, gasification and hydrothermal liquefaction may be suggested as better recycling options for thermosets while pyrolysis may be a good option for thermoplastics.
- Types of polymers in the stream.
  However, both thermoplastics and thermosets may belong, for instance, to the polyester group and be, thus, suitable for recycling through hydrolysis or other solvolysis methods. That is why information about types of polymers present in the stream is more desirable as attractive opportunities for recycling will not be overlooked. Knowing types of polymers also gives valuable information about possible presence of Cl, Br, etc. Unfortunately, this information is usually only partly available and/or difficult to acquire.
- Application the material was used in.
  This information can be used as an alternative way to get information on possible types of polymers, presence of Cl, Br, etc. if the direct information is not available.
- Polymer content.
- Moisture content.
- Additives - wood, metals, fibres, biomass, ash, etc.
- Particle size.
- Available amounts.
- Geographic location.
- What kind(s) of products are desired?
  This information is needed not only to create closed loops but for market building purposes.

Analysis of the input data

Examples of the "decision-making steps" in the selection process:

- Thermoplastics - produce only gas and oils when heated. Pyrolysis may be a potentially attractive recycling option.
- Thermosets - form solid residue (carbon) when heated, gasification and hydrothermal liquefaction may be considered as better recycling options.

- Presence of oxygen and/or nitrogen in thermoplastics (for example PET) - tend to form solid compounds in products / product will be unstable (catalyst or post-treatments may be needed).
- Presence of Cl and/or Br in the material - corrosive, produce hazardous emissions / extra cleaning steps will be needed, probably gasification (cleaning gas is easier than cleaning liquids).
- Ash and metals (for example Zn) can end in the gas phase when heated - require additional cleaning.
- High moisture content - only steam gasification or hydrothermal liquefaction can be used without prior drying.
- High content of PVC - low-temperature pre-treatment to release Cl is needed.
- Polyesters / nylon / lignin - chemical depolymerization is possible. Processes for depolymerization of nylon and polyester have a significantly higher TRL level than lignin depolymerization processes.

Output data to support the decision-making

- Technological solutions that can be tested.
- Possible pre-treatments that are needed – washing, sorting, fragmentation, de-chlorination, etc.
- Carbon content recovered in form of usable products.
- CO_2 per kg of input material / CO_2 per MJ of input material / CO_2 per unit recovered carbon.
- Hazardous compounds in the residues (type, amount and form).
- The amount and form of non-hazardous residues.

Selecting most resource-efficient solutions

An open discussion on the selection criteria that may/should be used has been carried out in the framework of the workshop. The following criteria have been proposed:

- Maximized recovery of non-renewable resources
- Maximized recovery of carbon per unit energy consumed
- Minimized CO_2 emission per unit carbon recovered
- No hazardous contaminants/emissions/residues
- Minimum rejects
- Best energy balance in relation to recovered material (or C)
- Versatile use of products

Economic Sustainability

An important function of the proposed tool can be to improve the economy of recycling through creating opportunities for combining multiple flows and supporting market for secondary products. This can create possibility to use advanced processing methods for small material flows and to use more resource-efficient processing methods by decoupling the method choice from own product needs.

Testbed

One of the objectives in the projects was to describe a long term model for a possible test bed function for feedstock recycling. Two main options were compared. One was a specific location and one main technology, using a larger demonstration plant that should be close to production. The other was to utilize the already existing infrastructure of facilities, primarily in Sweden, and that the test bed would be operated as a communicating and connecting function. Each strategy has their advantages and drawbacks. In the short term, it is needed with supporting funding, typically from national or regional incentives. To support the larger demonstration plant, it is needed to have it closely connected to both a receiving company of the products and also to companies/organization that will ensure the supply of needed feedstock. The distributed alternative with central node is not as dependent on the large flows of material for this specific purpose and in many cases the test equipment can be utilized for other feedstocks as well. However, it could be more difficult to prove the high technological readiness level. The latter suggestion is depended on a supporting body but would be able to survive and grow on less funding. It was not possible within the project to distinguish which of the two models that would be best in the short and long run. However, it is important to ensure a possible development with several techniques and possible outcomes (initial products).

Conclusions and next step

The main objectives of the project were to create a networking arena as well as to analyze current state of the innovation area for feedstock recycling and identify measures necessary to support and facilitate the innovation process. These objectives have been achieved successfully.

The offered networking opportunities proved to be demanded by stakeholders. The ultimate importance of networking was also pointed out by the results of the performed analysis of the innovation system.

The identified necessary actions and how they contribute to the vision of resource-efficient circulation of polymers in the future are presented in the logic model below, see Figure 8.

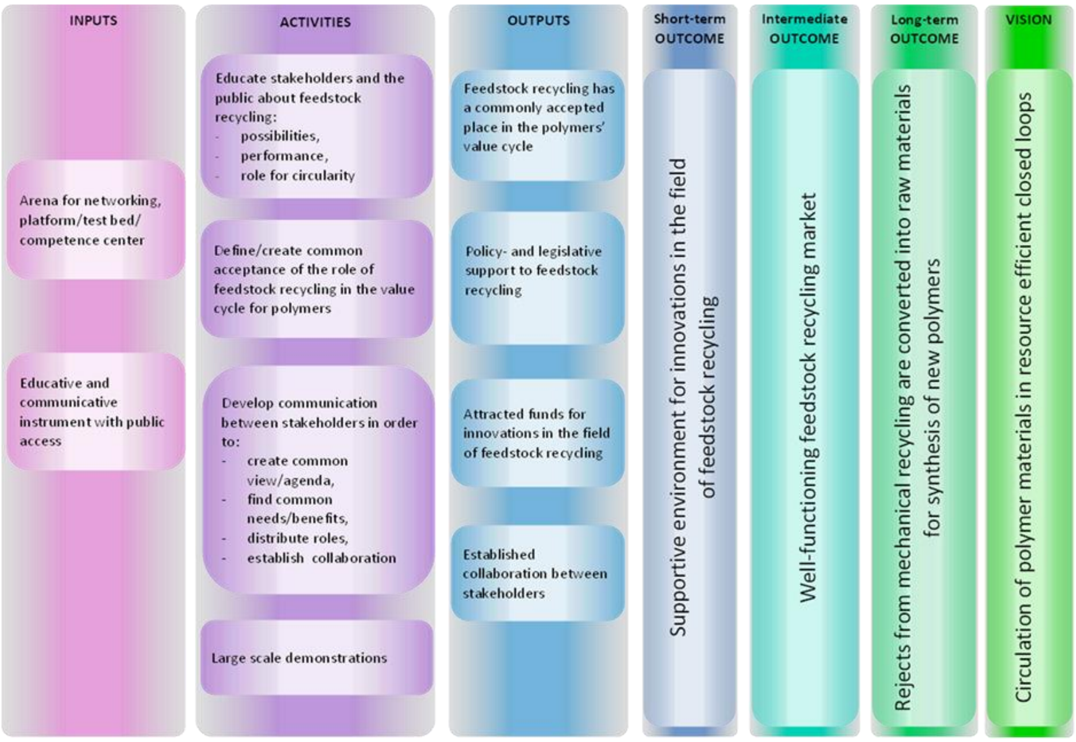

Figure 8 Logic model for further development of the innovation area "Feedstock recycling"

Consequently, the next step in improving the innovation environment in the area should be to create a formal structure (a platform or competence center) that unites actors and is suitable for the following functions:

- act as a channel to disseminate knowledge on feedstock recycling among stakeholders, authorities and the public,
- serve as an arena for communication and collaboration between stakeholders,
- represent feedstock recycling in societal processes and contribute to the common acceptance of its role in the polymers' value cycle,
- attract funds to enable innovations (in later stages).

Equipping this structure with an educational and communicative instrument available to all stakeholders would be of additional value for further development.

It should be noted that as pure fractions thermoplastics are possible to material recycle and thus represent a material value they will be more difficult to directly include in any feedstock recycling projects. However, the mechanical recycling processes used for the thermoplastics deteriorate the properties and eventually these plastics have to be recycled in another way. This is not the case for thermosets or mixed fractions of thermoplastics where no good mechanical recycling process is found.

Publications

L. Smuk and T. Richards, "Closing the loop for polymer materials, Feedstock recycling – opportunities and limitations", Circular Materials Conference, March 7-8 2018, Gothenburg, Sweden (see APPENDIX 3)

Project communication

Information about this project has been actively shared first through communication with stakeholders during preparation phase and before the first workshop, all stakeholders' groups were contacted. The project has been presented at numerous internal (RISE) and external meetings, mainly to researchers and companies working with polymer technologies and recycling of polymers. This includes Polymernod meetings, RISE Competence Platform for Circular Economy, planning meetings for EU project applications (partners from 6 EU countries), etc.

Bilagor

APPENDIX 1 Feedstock recycling of plastics

APPENDIX 2 CORTUS test procedure

APPENDIX 3 Presentation CMC 2018