CloseLoop – final report

Using the principles of circular economy is one way to exploit limited resources more efficiently. The CloseLoop project looked at the potential of the circular economy in Finland, both at a systemic level and in terms of technology development, focusing on high-value-added metals. The transition to a circular economy is a systemic change, with changes in production structures, business models, products and consumption practices. Cooperation, knowledge, and education play a key role. Co-operation of key actors is needed for the achievement of circular economy objectives. Circular economy development requires new tools and policies for the communication between businesses and the public sector.

The CloseLoop project has developed a new version of the Lifecycle Analysis (LCA), which allows multi-operator concurrent LCA assessment. There are plenty of different technologies behind the realisation of the circular economy vision. The project explored and developed new recycling processes, utilization of industrial residues, substitution of critical materials and further use of the recovered raw materials.

Research implementation and results

The modern society is based on products containing complex hybrid materials which are optimized for the use phase performance but which are difficult to repair or recycle. The state-of-the-art performance can rely on scarce materials many of which has been classified as critical raw materials (CRM) by European Commission. Such product can be found in e.g. ICT, transportation and energy sectors. Both new technologies and system level changes are needed to transform the state-of-the-art linear economy to a circular one. In the CloseLoop project, a holistic approach was taken to study circular economy of high-value-added materials, especially ceramics and non-ferrous metals. Detailed case studies focused on Li-ion batteries and thermoelectric generators.

The system level approaches included:

- Local and national ecosystems
- Business models
- Consumer behavior
- Multiscale modelling of circular systems
- Strategic foresight

The technology development comprised:

- Optimization of liberation and recovery of metals from the selected products
- Modelling of the recycling processes
- Substitution of critical raw materials in the selected products
- Valorization of industrial residues

Local and national ecosystems

Moving from linear to circular economy can require radical social and economic changes both at local, national and global level. New kinds of cooperation are needed to cope with the risks and make the best of the emerging opportunities in the transition period. A value creation tool developed at the Industrial Sustainability Unit of Cambridge University was applied to three Finnish regions (Pori, Kokkola and Lappeenranta) in local workshops. Participants from local cities, universities and industries co-created ideas about how to promote circular economy within the region and how to capture most value from the transition. The results were presented to different ministries and other national organizations in a final workshop.

Common topics identified in all the workshops were:

- Possibilities for brand building
- Importance of knowledge sharing
- Importance of new skills, education and life-long learning
- Challenges in innovating, testing and commercializing new ideas and concepts

Cooperation, knowledge sharing and education play key roles in circular economy. A trustworthy and neutral CE coordinator could promote cooperation between different organizations and sectors of the society.

Business models

New business models are needed to promote circular economy. Sustainable businesses should create value not only to the customer, but also to the environment and the society. A transition from product based to service based businesses can be foreseen. The sales, technical approach and product ownership could be replaced by lease of the product supplemented by value added services. Digital tools can be efficiently used to monitor the location, performance and maintenance needs of the product. New business models like leasing contracts, subscription fees or full service contracts, e.g. mobility as a service (MAAS), can be applied for the value creation. Sharing digital platforms are one emerging business model. New tools and concepts are needed for the companies to develop their CE business models.

Consumer behavior

Consumers play a central role in circular economy. However, this role is hardly recognized in political decision made in Europe. We compared the consumer expectations and CE policy approaches in different EU countries.

The key policy approaches identified were:

- Improved waste management
- Economic policy instruments
- Waste as a resource
- Bioeconomy
- Resource efficient design and production

The two first ones had good match with the consumer expectations. However, the consumers are relating circular economy more closely with energy policy and climate change than political actors. Moreover, social dimensions like equal opportunities, universal accessibility as well as human and environmental health appear to be missing from the political discussion.

The circular economy preferences of Finnish people were polled with a questionnaire addressed to 1555 citizens. The results show that the Finns prefer recycling and repairs to sharing economy. Women, elderly and middle to upper class people recycle their products more frequently than others do. Services are preferred for the repairs and maintenance of products like household appliances, electronics and vehicles. Self-service is more common in maintenance of houses.

Multiscale modelling of circular systems

As the transition to circular economy requires multidisciplinary approaches, new mathematical and digital tools are required to address the complex systems. The CloseLoop approach to this challenge has been a digital workspace called as Modelling Factory where material and process designer, company representatives and political decision makers can co-create, quantitatively assess and optimize complex, multidisciplinary problems.

Moreover, new communication tools are needed for sharing information between the actors in circular ecosystems. The Modelling Factory provides tools for sharing confidential information with a trusted operator who can e.g. perform Life Cycle Assessment (LCA) within a whole multi-actor value chain (or value circle) without sharing critical information with the other actors in the value chain. This tool titled as "Network-LCA" can be used, for example, tracing the flow of critical raw materials within the ecosystem. It was demonstrated to study the LCA of electric vehicles and their batteries in a workshop organized in cooperation with EIT RawMaterials in May 2018.

Strategic foresight

According to another poll carried out by the CloseLoop project, companies play a key role in the promotion of the circular economy. Investments to new technologies and business models are needed by the companies and they can also require sustainable solutions form their suppliers. How much the companies are able and willing to invest depends on the overall development of the global and national economy.

Three economic scenarios and their effects on circular economy were studied in CloseLoop:

- Slow European Growth
- Climate Crisis
- The World According to Agenda 2030

The first scenario requires development of technologies for extraction of materials from low concentration primary and secondary sources. Decrease in the purchasing power of middle class can promote different service and sharing economy concepts. In the second scenario, renewable energy and resource efficient technologies are promoted. New, strict regulations are introduced to cut down the emissions. Care should be taken that these regulations do not hamper innovative recycling and reuse concepts. In the last scenario, there is abundant renewable energy available and biomass is no more needed for energy production. The available biomass resources can be used for food and renewable chemical production. There may be severe lack of critical raw materials, and different sectors of the society need to fight over them. Substitution of the CRMs becomes important but may shift the criticality to new materials.

Optimization of liberation and recovery of metals

Following the rapidly growing interest in the production of Li-ion and NiMH batteries for electric vehicles and grid-scale energy storage, improved recycling processes are urgently needed to prepare for the large-scale application of these resource intensive technologies. In the CloseLoop project, liberation and recovery processes were developed for rear earth elements in NiMH batteries as well as Co, Ni, Cu and Li in Li-ion batteries. Both mechanical shredding and sieving as well as hydrometallurgical leaching and recovery unit processes as well as their combinations were optimized. New Li-ion coin cells were assembled using the recovered materials, and their properties were compared with reference cells made using pristine raw materials. The importance of battery raw materials and recycling for Finland was communicated to the Finnish authorities and industries. This led to an industry driven follow-up project BATCircle funded by Business Finland.

Recycling options for state-of-the-art Bi_2Te_2-based thermoelectric converters was also studied. Commercial TE modules were disassembled, milled and sieved and enrichment of different materials (semiconductors, metals, plastics) in different sieve fractions evaluated. The milling conditions have been optimized for efficient preprocessing of TE module recycling. The semiconductor and metal powders can be further processed by other metallurgical methods.

Ideas were created for the recycling of organic Li-ion batteries and CRM-free thermoelectrics. However, these concepts could not be experimentally verified due to too small amounts of materials produced for the new approaches.

Modelling of the recycling processes

The recycling processes were modelled using the following approaches:

- Brunauer-Emmet-Teller (BET) approach to simulate concentrated aqueous solutions in a multiphase Gibbs free energy model. The Gibbs'ian BET technique can be used in conjunction with conventional aqueous solution models, to significantly improve the scope of simulation of hydrometallurgical processes.
- Statistical entropy analysis as a circularity parameter for optimization and evaluation of recycling processes. This method has been successfully applied to the mechanical processing of both Li-ion batteries and TE modules.
- Flow sheeting of unit operations in recycling (HSC?).
- Network LCA, see section 1.4.

Substitution of critical raw materials

Substitution of critical raw materials were studied for three renewable energy related applications:

- Li-ion batteries
- Thermoelectric modules
- Polymer electrolyte membrane (PEM) water electrolysis

In the field of Li-ion batteries, transition metal and flammable organic electrolyte containing state-of-the-art materials were substituted by organic electrode materials and a solid-state-electrolyte. As the electronic conductivity of the organic electrode materials and the ionic conductivity of the solid state electrolyte are poor, the materials were applied as thin films using atomic and molecular layer deposition techniques (ALD/MLD). A thin film microbattery was successfully demonstrated and a patent was filed for the concept.

In the field of thermoelectric energy conversion, we developed novel simulation methodology for predicting the thermal conductivity of the materials. The new methods enable accurate prediction of thermal conductivity for transition metal oxides that were not possible to investigate previously. This predictive capability enables systematic improvement of the thermoelectric energy conversion properties of transition metal oxides composed of earth-abundant elements. These materials could replace state-of-the-art-materials, which are rare or toxic like telluride and lead.

In the field of PEM electrolysis, it is not possible to totally replace platinum group metals (PGM) for the oxygen (OER) and hydrogen (HER) evolution reactions. We studied these reaction using density functional theory (DFT) modelling and different experimental approaches. The platinum loading of the HER reaction could be decreased by an order of magnitude by using a novel carbon nanotube based catalyst. A patent application was filed for the concept.

Valorization of industrial residues

Potential industrial residues were screened as raw materials for high-value applications. Mining tailings and steel slags were identified as potential raw materials for high temperature thermal and electric insulation materials. As optimization of the composition and particle size are crucial in the ceramics processing, milling of the residues and use of additives was needed for optimal process conditions.

Alumino-silicate based mining tailings were successfully used as raw material in the synthesis of refractory ceramics which could withstand temperatures up to 1450 °C. Ferrochrome slags were also applied as raw materials for refractory ceramics.