Final Report Summary - RECLAIM (Reclamation of Gallium, Indium and Rare-Earth Elements from Photovoltaics, Solid-State Lighting and Electronics Waste)

Executive Summary:
RECLAIM’s main objective was the reclamation of indium, gallium, yttrium and europium Photovoltaics, Solid-State Lighting and Electronics waste. Within the four years duration of the project (2013-2016), two recycling technologies have been developed until pilot scale plant and one technology to demonstrator scale:
• The first pilot plant is developed for the recovery of yttrium and europium from spent fluorescent lamps
powders. This plant has been built and operated at Técnicas Reunidas Technology Centre (Spain). The production rate is shown to be 2256 g/day of Yttrium and 127 g/day of Europium from the collected powder.

- The second pilot plant demonstrates the recovery of indium and gallium from Flat Panel Displays and CIGS PV panels. It has been constructed and commissioned at the Coolrec site in Tisselt, Belgium. The hydrometallurgical part of the process was developed by Suez Water (Venlo, NL) and shows that indium can be recovered up to 10 g/day (8 hours/day). Data are not yet available for Gallium.
- Finally, SAT has demonstrated the technical feasibility of a quick and low-cost removal of components from PCBs. Only a vision system, selective infrared heating removal and storage for different components (according to material content for further processing) are necessary for this process.

The Reclaim consortium is interested in making available to third parties the technologies developed under the project in several ways:

a) Sale of Know How:
   - TNO will make patented hydrometallurgical technology available under license conditions. Consortium partners are preferred partners.
   - Coolrec and Indumetal will make process technology available within 500 km from its own locations.

b) Sale of equipment: Ondeo/Suez Water sells hydrometallurgical process equipment for recovery of indium and gallium.

c) Toll processing: Coolrec, Indumetal, Relight process WEEE on agreed terms.

d) Joint research: partners will contribute RECLAIM Foreground to new research projects on terms to be agreed.

Third parties interested in any of the above should in the first instance contact:
TNO (NL) – Toon Ansems
SAT (AT) – Bernd Kopacek

Further information and contact details can be found on [www.re-claim.eu](http://www.re-claim.eu).

Project Context and Objectives:
Emerging green technologies such as photovoltaics (PV) and solid-state lighting (SSL) heavily depend on the use of raw materials like gallium, indium and rare-earth elements. It is expected that global supply of gallium and indium will increasingly lag behind on demand if the current circumstances persist. The growing demand is driven by PV, SSL (notably light-emitting diodes, or LEDs) and electronics (integrated circuits) for gallium and by PV and electronics (liquid-crystal displays, or LCDs) for indium. Meanwhile the primary production and trade of these materials is highly controlled by a few countries and particularly by China. A further complication for both gallium and indium is that they are mined as by-products of other materials.

The group of the rare earths (RE) consists of yttrium, scandium, and the so-called lanthanides, e.g. europium. For rare-earth elements a similar tight situation exists with global annual demand being projected to rise to 170,000–190,000 tonnes by 2014 and associated Chinese production of 160,000–170,000 tonnes being subject to export cuts. Various sources estimate that phosphors represent 4 to 15% of the rare-earth market, with the most recent estimates ranging from 7 to 11%. Within this sub-group, there are three main applications: televisions (plasma, liquid-crystal display and cathode-ray tube),
fluorescent lamps, and X-ray intensifying screens, with currently few – if any – suitable substitutes for the used phosphors available. As an example of how critical market conditions currently are, the rare-earth tri-phosphor in a general-service fluorescent lamp can be the highest material cost component (depending on the lamp type). With yttrium and europium being the most important rare earths for lighting applications, this places a particular emphasis on the availability of these specific key metals.

The previous obviously poses a problem as it renders Europe particularly susceptible for the provision of these increasingly scarce materials that are crucial for meeting policies on energy renewability and energy saving as well as for the further development of these sectors with apparent economical and employment implications. This is also expressed by a recent EC report that qualifies gallium, indium and rare earths to be the numbers one, two and four in terms of criticality for emerging technologies in the long term (2030).

The situation for gallium and indium on the one and rare-earth elements on the other hand is somewhat different though, as the former are almost exclusively used in electronics (including PV and SSL) while the latter also have several other applications (including metallurgy, magnets, catalysts and polishing agents). Recycling systems to reclaim these materials from waste from electrical and electronic equipment (WEEE, or E-waste) such as TV sets, computers and mobile phones are not yet in place which severely challenges the sustainability of these technologies. Further to that, one of the main barriers to virgin sources of such key metals is in the time delay for starting up new mines (or reviving existing ones) due to their capital-intensive nature and the regulatory requirements. Reports by USGS show that it takes between 2 and 17 years (with an average of just below 10 years) from the start of the (post-exploration) process to commercial production.

Hence there is a strong need to establish recycling systems for PV, SSL as well as for other electronic waste to reclaim gallium, indium and rare-earth elements and capitalise on these as yet unexploited and growing deposits of key metals.

Current bottlenecks are in the isolation of the parts with the targeted materials from the waste and in the extraction and purification of these materials to bring them back to specification. More in particular, the concerned materials tend to be used as compounds (gallium arsenide, gallium nitride, indium oxide) rather than in their elemental form and as thin layers on substrates in overall very low amounts. Further, recycling of discarded products will have to handle multiple sources of waste of various and undefined compositions.

The prospective recycling technology from the RECLAIM project should be able to reclaim the targeted materials from present and future e-waste, be it in the metallic form or in compounds (oxides, sulphates, nitrates or phosphates), depending on the specific requirements for re-use. Boundary conditions for the processes to be developed are that they are apt to fit in an industrial context and are environmentally compliant (to the European situation). Sub-targets:

- Separation processes for the disassembly, disconnection and sorting of E-waste to isolate the parts containing the targeted materials, including proper identification techniques (80% separation efficiency).
- Dissolution and recovery processes for the selective extraction of the targeted materials from their carriers (reclamation efficiency for gallium, indium, yttrium and europium >95%).
- Concentration and purification processes to remove undesired contaminations from the targeted materials and bring them to specification for renewed use (purity for gallium 99.99%, indium 99.99%, and yttrium and europium 99–99.9%).
- Impact: Eco-efficiency profiles for high-value recycling routes that give directions for optimal closed-loop recycling, including that on a regional scale.
Pilot implementation of a recycling facility in an industrial setting with newly developed unit operations for separation, dissolution/recovery and concentration/purification for selected waste streams on a pre-production scale (output: 5–15 g/day for gallium and indium and 30–100 g/day for yttrium and europium oxide).

- Economically viable technological solutions that relieve current bottlenecks hampering recycling of gallium, indium and the rare-earth elements yttrium and europium.

Project Results:

1.3.1 Selection of specific waste streams

The first project activity was to come to a selection of specific waste streams that contain relative high amounts of the targeted key metals (In, Ga, Y and Eu) on the basis of characterisation of current and anticipated electronic waste.

The overall conclusion was, that the waste streams with the best combination of metal volume and the likelihood of being successful, would be (1) flat panel displays, (2) printed circuit boards, (3) energy efficient lighting and (4) high efficient solar cells (CIGS).

However, because none of the targeted metals is available in enough quantities in the PCB stream, it was decided to only perform further research and demonstration on disconnection, recognition and sorting for this waste stream. These technologies can be very interesting for other (valuable) materials as well.

FRANCISCO ALBERO SAU (FAE), as an end user of the recycled material, gave initial information to the recyclers about the form, quantity and quality that the recycled samples has to meet in order to introduce yttrium in their process of fabrication of ceramic brakes fabrication and indium and gallium in their process of fabrication of thin film photovoltaic cells, respectively.

1.3.2 Printed circuit boards

State-of-the-art on pre-treatment routes for PCBs reports that they are based on manual dismantling, followed by shredding and, occasionally, mechanical sorting. This feasible recycling method is shown as a process without environmental pollution, no high investment required, low operational costs and low energy costs. The printed circuit board concentrates obtained from this pre-treatment are currently focused on copper and precious metal recovery.

In order to concentrate these metals, and leaving the state-of-the-art aside for the moment, the RECLAIM consortium has studied other options like the study of disconnection and sorting of the components present on the boards. The assessment of the costs, productivity, feasibility, etc. of this new path that has been decided to investigate might not be rival for the current state-of-the-art, but it is necessary to assess in order to have an alternative and think up new ideas that can be applied in the future.

Sorting

Sorting activities focused on the automatic optical recognition of characteristics of PCBs that are prerequisite for sorting. These characteristics include PCB size and shape, source (PCs or FPDs), the number and locations of mounted components such as IC chips, and the specific PCB model.

At first, CVL and CogVis investigated the feasibility of different types of optical sensors for analysing PCBs at the overall and component level. For this purpose, an acquisition system was built. This system integrates the tested sensors, a conveyor belt, a flexible illumination system, and means for blocking outside light.

In summary, it was concluded that the final image acquisition system should contain two RGB cameras,
one IP camera (such as the tested Axis camera) for continuous analysis of waste streams and one high-resolution but low-framerate DSLR camera (such as the tested Nikon camera) for situations in which high-quality images are required (i.e. for analysis at the component level).

The recycling partners agreed that a system for recognizing specific PCBs in waste streams would be beneficial for recycling purposes. Usage examples include automatic sorting of PCB streams that are known to frequently contain specific PCBs, as well as automatic separation of PCBs that are known to be valuable or hazardous (or should be treated separately from the rest for other reasons). CVL and CogVis investigated different approaches for PCB recognition and developed an application that can perform this task reliably and in real-time, despite challenges such as dust and partial PCB damage. The application is easy to use by means of a graphical user interface. A video was created by CVL and CogVis that explains and demonstrates the application.

Furthermore, the recycling partners expressed that the origin of a PCB – whether it comes from a PC or a FPD – is beneficial for sorting/recycling due to the different component compositions. For this purpose, CVL and CogVis compiled a dataset of IP camera images of 165 different PCBs from PCs and FPDs that were provided by the recycling partners. On this basis, approaches for predicting the PCB origin from images were investigated. After initial studies, CVL and CogVis developed a method for this purpose that considers both geometrical properties such as PCB size, as well as PCB appearance. The appearance-based prediction makes use of Deep Learning, a state-of-the-art approach to visual analysis. The results obtained on the IP camera dataset suggest that the PCB origin can be predicted with an accuracy of up to 90%, depending on the PCB conditions. A video was created that explains and demonstrates this method. The partners also agreed that IC chip counts are an important criterion for sorting. CVL and CogVis thus studied possible methods for the automatic counting of IC chips in images of PCBs. To be able to validate such methods, a dataset of high-resolution DSLR images of the same 165 PCBs was created and the location of all IC chips were manually labelled in every image. CVL and CogVis then developed a method that is able to both count and localize IC chips accurately and in real-time. The average counting error on the aforementioned dataset is 2.5 (the actual number of IC chips varies between 0 and 135). The method uses video data from the IP camera to detect and track individual PCBs as they move along the conveyor belt, and automatically triggers the DSLR camera to capture a single high-quality image of every PCB at the correct time. This high-resolution image is then analysed for IC chip counting. A video was created that shows how this application works in practice.

Disconnection

New ways of disconnection have been researched by TNO in order to know the possibilities to remove components (in general and pre-selected) form the boards as a away of enriching key metals in a concentrate. The first method is to achieve a sudden temperature increase of the PCB to 250 ºC by placing it in a liquid, since the heat transfer between liquid and PCB is much more efficient than between air and PCB. As liquid, molten salt is chosen. Another way to elevate the temperature of the PCB to 250 degrees is the use of hot air. This will take more time and is less efficient. Therefore the time in the machine has to be longer and the process will have a longer cycle time.

A cost evaluation showed that the costs of a salt bath concept will be significantly higher than a concept based on hot air or infrared because less strict requirements on the materials used and less functions are required as explained earlier. Since no clear business case is available yet it is not possible to specify the exact requirements for such a machine.

1.3.3 Yttrium & Europium recovery from EEL lamps
1.3.3.1 Classification
Lamps have to be removed from any separately collected WEEE. During handling and storage special attention should be given to the breakage of lamps and avoid damage. Then, they need to be sorted: Energy Efficient Lighting (EEL) and other lamps (HIDs, LEDS, etc.). Within EEL types, it can also be one extra classification step with the objective of separating Linear (LFL) or Compact fluorescent lamps (CFL). Depending on the company, both streams can be treated separately in homogeneous batches: LFL or CFL.

1.3.3.2 Disconnection and Separation
In order to obtain an Yttrium and Europium rich fluorescent powder from fluorescent lamps, current state of processes for the removal of mercury are evaluated. European legislations sets, that removal is obliged above a certain limit. Currently, mainly two different industrial processes are being used by recyclers within Europe:
- End cut technology
- Crush and sieving technology
Both from economical as productivity point of view, the crush and sieving technologies are the most interesting ones from an industrial point of view, particularly, in industries with high treatment capacities. So, this technology has been selected as starting point for Y/Eu recovery.

After the classification step, the treatment consists of a mechanical process to crush the glass and thereby, be able to remove the tube ends (metallic or plastic parts) by means of a magnetic and eddy current separation. By sieving, the glass and fluorescent powder are separated. All the process runs in an automated and isolated line, including an industrial vacuum cleaner with active carbon filters, to assure the capture of mercury. From several trials and analysis it has been concluded that the fluorescent powder fraction obtained from this processing is ready to enter the hydrometallurgical recovery process.

1.3.3.3 Hydrometallurgical process for the recovery of Y and Eu
After a thorough study of various alternatives it has been defined that the process for the recovery of the targeted elements should consists of three sequential key steps:
1- Pretreatment Stage: The goal of this stage is to selectively dissolve Calcium from spent fluorescent lamps minimizing any losses of Yttrium and Europium. Calcium is considered a contaminant of the final product produced downstream in the process and therefore its elimination upstream is crucial to produce a marketable Y/Eu concentrate.

2- Leaching Stage: The objective of this step is to selectively solubilize the targeted elements from the Y/Eu enriched solid produced in the pretreatment stage. Operation of this stage has been defined so as to minimize reagents consumptions while optimizing solubilisation efficiencies.

3- Precipitation Stage: The aim of this unit is to selectively precipitate Y and Eu from the pregnant liquor solution from the leaching stage in order to produce the best possible marketable Y and Eu concentrate.

1.3.3.4 Pilot line
Based on the previously described research, a pilot line has been built for the demonstration of the developed recycling process for the recovery of yttrium and europium from spent fluorescent lamps powders. The pilot plant was operated at Técnicas Reunidas (TR) Technology Centre, with Pretreatment, Leaching, Neutralization and Precipitation Units, by TR and the punctual collaboration of RELIGHT´s staff.
A brief description of the different units that were operated is:

**Pretreatment Unit**
The goal of the pretreatment stage is to selectively dissolve Calcium from spent fluorescent lamps dust, minimizing any losses of Yttrium and Europium. Calcium is considered a contaminant of the final product and therefore its elimination is crucial to produce a marketable Y/Eu concentrate. This unit was operated in two different periods of four days, 24 hours per day (3 working shifts).

A total of 415 kg of spent fluorescent lamps dust were processed in the pretreatment unit yielding a total of 235 kg of REE concentrate suitable for the feeding of the leaching, neutralization and precipitation units.

**Leaching Unit**
The objective of this step is to selectively solubilize the targeted elements from the Y/Eu enriched solid produced in the pretreatment stage. Operation of this stage has been defined in order to minimize reagents consumptions while optimizing solubilisation efficiencies.

Also this units was operated in three different periods of five days, 24 hours per day (3 working shifts).

**Neutralization and Precipitation Unit**
The aim of this unit is to selectively precipitate Y and Eu from the pregnant liquor solution produced in the leaching stage, in order to have the best possible marketable Y and Eu concentrate.

This unit was operated in two different campaigns for four days each, 24 hours per day. Around 95 Kg of REE concentrate were processed in the first campaign and approximately 104 Kg in the second campaign.

It can be concluded from the performance of the pilot plant that overall production has been achieved:

- 2256 g /day of Yttrium
- 127 g/day of Europium

Comparing with the objective of the pilot plant (production between 30-100 g/day of rare earths), it can be concluded that the performance of the pilot plant for the recovery of Y and Eu from spent fluorescent lamps has accomplished the targeted objectives by far.

The overall recovery yield when coupling pretreatment, leaching, neutralization and precipitation results of Campaign #1 were 70 % for Yttrium and 57% for Europium in respect to the content of both elements in the raw material.

With regard to the importance of each item in the total cost, more than half of the total cost corresponds to chemical reagents (51%) although services cost is similar (44%). This is mainly due to nitric acid in chemical pretreatment and electric power consumption.

1.3.3.5 Evaluation of recovered Y/Eu material for use in new products

The material from the Y/Eu recovery line has been validated for use in two different applications:

- Yttrium oxide as co-firing agent in the preparation process of advanced ceramic material like SiC for tablet brake application,
- Ni electrode fabrication.

**Brakes tablets**

Validation of the final product from the pilot plant was carried out for a real application by FAE. Yttrium oxide was used as a co-firing agent during manufacturing advanced ceramic brakes tablets for automotive
Tape casting technology is used to deposit ceramic films. Those films are stacked and cut until the desired thickness. To obtain the final product, sintering of the ceramics is carried out by applying pressure and temperature. Once brakes are fabricated, mechanical and tribological studies are carried out to determine the final product properties.

During the ceramic brakes manufacturing process, one of the most important stages is the formulation of ceramic slurries. Compositional studies of the recycled materials were carried out by Energy dispersed energy and scanning electron microscope (EDS/SEM) technologies. Thermal behaviour of the recovered powders were also carried out by thermogravimetric with differential scanning calorimetry (TGA/DSC). The ceramic slurries were formulated adding some additives such as dispersants and polymeric binders. Yttrium oxide was added, as a co-firing agent, in order to reduce the temperature of sintering of the final material. Monitoring of the stability of the slurry formulation was carried out during one week, by measuring the pH and the viscosity before and after the addition of the different additives.

Summary of the main conclusions obtained from the study of slurry formulation:

• The use of yttrium sulphate involves decomposition stages at high temperature, compromising the process because of excess processing times and energy waste.
• Yttrium carbonate is suitable for the application because it decomposes to yttrium oxides at low temperatures.
• The slurry stability is governed by the content of Ca2+ and the presence or absence of the flocculant additive during hydrometallurgical process for the recovery of yttrium.

Sintering process was carried out with SPS (Spark plasma sintering) equipment. As a result of the sintering process, the ceramic tablets based of SiC were obtained.

Looking at the result when co-firing material (Yttrium carbonate) from pilot plant is used, we can say that the brake tablets obtained have similar properties as reference brake tablets made with commercial or reference material. Thus can be concluded that, by using recycled materials, it is possible to fabricate advanced ceramic tablet brakes for automotive application.

Ni electrode fabrication

The high-temperature performance of nickel metal hydride (Ni/MH) batteries has been improved using the addition of yttrium as doped element in the lattice of the spherical nickel hydroxide powder Ni(OH)2 used for the positive electrode. The crystal structure of yttrium-doped nickel hydroxide powder is similar to that of regular nickel hydroxide powder. The charge acceptance of the Ni/MH battery in a range of temperature at 40-60 ºC is about 70% with the addition of yttrium. The measured specific capacity of yttrium-doped Ni(OH)2 powder is much higher than that of the regular spherical Ni(OH)2 powder. The yttrium-doped nickel hydroxide active material remarkably improves the high-temperature charge/ discharge efficiency.

According to bibliography, Yttrium oxide enhances the discharge capacity due to increase of over potential in the evolution of oxygen making better the charge. So as to check this axiom, TR in collaboration with electrochemical research groups has been carrying out several experiments at 40 ºC comparing commercial Yttrium oxide versus Recycled Yttrium oxide from Pilot Line.

TR’s Electrochemical Research Group has observed similar chemical behaviour Ni Electrodes using both types of Y2O3 as dopant material.

The addition of yttrium in the nickel hydroxide lattice improves the high temperature performance for the traction-use Ni-MH batteries, especially for hybrid electric vehicle applications and it is clear that the use of recycled yttrium oxide, obtained from pilot line in RECLAIM project, can ensure the same effect in this...
type of electrodes applied evenly on Ni/MH batteries. The spherical Ni(OH)₂ powder doped with Recycled Yttrium in the nickel hydroxide lattice has a similar high-temperature charge/discharge performance respect to Commercial Yttrium in the nickel hydroxide lattice.

1.3.4 Indium and gallium recovery from FPD and CIGS panels

Flat panel displays (FPD) and CIGS type PV cells were selected as potential source material for the recovery of indium (from FPD and CIGS) and gallium (from CIGS).

1.3.4.1 Disconnection and separation of FPDs

Sorting

Analysis of different types of FPDs showed that the concentration of target metals in plasma screen FPDs is very low or neglectable compare to LCD screen FPDs. LCD (liquid crystal display) technology can use different backlighting: old cathode fluorescent backlighting (CCFL) and LED backlighting (LED). Both CCFL and LED FPDs have been studied with the aim of recovering Indium from the ITO layer of LCD televisions.

The backlight lamps represent 2% of the total mass of the LCD and contain mercury. If they are not previously extracted, the whole screen has to be treated as hazardous waste. In fact, making sure that the fractions produced by the LCD process are mercury free is extremely important. After dismantling the backlight unit, the remaining 98% of the mass can be easily treated in a conventional shredder for waste electronics or manually dismantled.

Currently, sorting between plasma TVs and the TFTs is done manually during the dismantling step of the casings from the general panel. This occurs at present due to low FPD volumes that do not encourage for automatic or semi-automatic pre-treatment processes' investment and implementation. Therefore, a parallel manual sorting does not impose much additional effort on workers and thus is considered satisfactory from a project standpoint. Nonetheless, a possibility of automatic recognition has been investigated as a concept formulation with future view.

Judging from images of different types of FPDs obtained by CVL/COGVIS, it was concluded that a reliable distinction between plasma and TFTs solely based on images is not possible. Also identification based on bar codes is not possible because there is no database of mappings from model or serial numbers to panel types available. CVL expects that an automatic sorting method can be designed that uses panel weight and thickness. Such a system would involve a scale (as well as means for automatically moving panels on/off the scale) and a depth sensor such as the Asus Xtion Pro Live for estimating the panel weight and thickness, respectively. These features would then be used for classifying purposes, and the predicted class (Plasma or TFT) would be used for automatic sorting.

For the future of recycling there is a possibility to urge manufacturers for inclusion of some features that can be recognised later in an easy way, so that end-of-life products’ recycling is facilitated and environmental risks reduced.

Disconnection

The state of the art of FPD recycling shows that mainly there are three different industrial processes are being carried out by recyclers in Europe:

a) Mechanical treatment: based on shredding the complete device followed by mechanical sorting of the fractions.

b) Manual dismantling: dismantling of stand and covers, PCBs, backlight tubes, taking apart the display panels to be shredded separately.
c) Semi-automatic treatment: partial dismantling of covers and PCBs, followed by a shredding of the remaining fraction (including the display panel); process developed by COOLREC.

These three processes have been performed by the recycler partners (COOLREC, RELIGHT and INDUMETAL), and different samples and rates have been obtained. From a quality point of view, the analysis carried out within project conclude that the manual process is the best to assure the quality of the product that currently it is required by the hydrometallurgical process. However, from an economical point of view a hybrid treatment is economically more feasible.

Thus, the development of a specific disconnection process has been consensuated with the aim of improving the quality of the fractions obtained from Coolrec’s process. Different tests have been conducted to check if sieving and/or use of magnets can lower the content of iron, aluminium and copper in the FPD material of the semi-automatic line. These experiments learned, that using different size sieves, thus retaining between 10 and 40% of the solid material, has no strong influence on the iron, aluminium and copper concentrations obtained after leaching the obtained FPD waste.

It can therefore conclude that pre-treatment by sieving and/or removal by magnet is not effective in to lower the iron, aluminium and copper concentrations in the PLS. The indium concentration in the PLS is approx. 300 mg/l, with iron and aluminium levels being up to 100 times higher. These high iron and aluminium concentrations will probably be technically manageable after purification, concentration and recovery of indium, but from an economic and environmental point of view these ratio will be not acceptable due to increased chemical usage and waste.

It has been agreed that for the pilot phase, fractions coming from the manual dismantled FPDs will be treated as preferred fractions in terms of quality. However, to check the chemical usage, waste generation and technical purification of a more industrialized process to run the plant with the FPD’s fractions from the semi-automatic line from Coolrec will be needed. This will generate enough data to be sure of our technical, environmental and economic evaluation.

1.3.4.2 Disconnection and separation of CIGS panels
End-of-life and rejected CIGS-panels at this moment are collected and stored for there is no process commercially available to recycle these kind of PV-modules. Their active layer, consisting of Copper, Indium, Gallium and Selenide (CIGS) contains the target materials Indium and Gallium. To make the CIGS-layer, which is trapped between EVA on glass at one side and Molybdenum on glass on the other side, available to further processing, mechanical and/or thermal treatment options could be applied.

Identification of CIGS panels
Currently, there is not any commercial option so to develop this kind of technology is a challenge for the Consortium. Therefore, preliminary experiments were carried out by CVL to investigate the technical feasibility of distinguishing between Crystalline Silicon (cSi) and CIGS panels using Computer Vision. The results indicate that this is possible based on colour, texture, or a combination. CVL advises to perform more experiments with more different types of panels in order to confirm this.

Disconnection and separation of the CIGS fraction
For the disconnection and separation of the CIGS panels, a specific series of processes has been selected from experimental work at Coolrec. Existing equipment can be used for these processes. The main findings are:

- The fine glass fraction from the course crushing (first step) does not contain CIGS.
- The aluminium back foil from the air separation (last step) contains only small percentages of CIGS.
• All other glass fractions, obtained in some way in the experiments, do contain CIGS, and can be treated in the chemical leaching process as well for Indium and Gallium recovery.
• Still it is recommended to remove the glass fraction after course crushing in order to keep the amount of material (especially the glass) in de spinner as small as possible (for efficiency).
• The flakes contain the largest fraction of CIGS.

1.3.4.3 Hydrometallurgical process for the recovery of indium and gallium

Based on the experiments performed within the project, most promising hydrometallurgical process steps are:
1- Leaching Stage: At this stage the raw materials (sorted FPD and pre-treated CIGS) are treated to remove the metals (including Gallium and Indium) from their carrier.
2- Purification and concentration Stage: The objective of this step is to selectively remove Indium and/or Gallium from the leachate solution and to make solutions enriched in Indium and Gallium for the recovery stage.
3- Electrochemical Recovery Stage: The aim of this unit is to recover the Indium and Gallium as pure metals.

Pilot line

The detailed engineering for all the equipment of the pilot unit for the recovery of Indium and Gallium from FPD and CIGS panels, including selection and purchasing of components, has been taken care of by Ondeo. With the equipment a containerized pilot unit is built at the Ondeo workshop. End of May 2016 the container is delivered to the Coolrec site at Tisselt in Belgium. The pilot is tested and started up in May/June 2106.

The pilot is a multi purpose unit able to treat different kind of E-wastes which contains Indium and/or Gallium as the recovered product. The unit is constructed in a 40 feet container and includes several operation steps with automatization. The plant can produce metallurgic Indium (from FPD) or metallic Indium and Gallium (from CIGS) in amounts of approximately 1 gram per hour.

The plant has been designed operating in a batch mode to handle the different incoming e-wastes and to be able to maximise the recovery of the individual process steps. The plant has been designed to operate 24 hours / day (or less if operations is only during day).

In the period of June – August the following types of waste have been treated:
• E-waste from FPD
  o Scratch from the ‘Hand sorted FPD lines’ were contaminations of iron, copper materials is minimum
  o Scratch from the ‘Semi-automatic FPD lines’ (@Coolrec)

• E-waste from CIGS.
  Before the action chemical processing the CIGS panels are mechanical pre-treated (frame removal, sieving, air separation, spinner).

Economic Evaluation for Ga/Indium recovery

Based on the work presented above, the economic evaluation of the recovery of Indium and/or Gallium from FPD and/or CIGS are described below for the hydrometallurgical unit.

Only part of the WEE material will be processed in the hydrometallurgical route after the pre-selection and sorting processes. Costs per ton of WEE are recalculated based on percentage which have to be
processed in the hydrometallurgical route.

- Operation cost (opex) are estimation to be confirmed by demo-plant
- Amortisation costs are calculated on 5 years investment (with 6% interest) and 16 hours/day operations
- ROI is calculated excluding pre-treatment (sorting, sieving etc.)
- Returns glass estimated on € 25,- / ton. Indium on € 45,- / kg. Gallium on € 175,- / kg

1.3.4.4 Evaluation of the recovered indium
The influence of several impurities on the performance of chalcopyrite solar cells has been investigated by FAE. In many cases, the performance of the devices was slightly affected and in some cases even improved with small quantities of impurities. The best results were obtained with impurities (and the used quantities) compared to the average value of the reference sample. Only the case with Fe impurity clearly exhibited worse performance.

This result is very important and clearly demonstrates that lower source material purity can be used for CIGS Photovoltaic fabrication and can be even beneficial if adequately controlled. This proves that recycling CIGS devices in the future could also ensure a supply of source materials for the same technology and since that very high purity is not necessary required, the consequent fabrication cost of recycled PV panels could be considerably reduced.

Characterization of indium salt received from ONDEO was evaluated, validating that the recycled samples does not contain any level of impurities that may have adversely influence in the optoelectronic behaviour of the solar cell.

1.3.5 Life cycle analysis and Life cycle costing
Several treatment routes with the recovering of critical metals have been compared on the basis of their economic and environmental impacts. This comparison has been performed using the Life Cycle Costing (LCC) and Life Cycle Assessment methodologies. Combining the results of both assessments in en Eco-efficiency graph it becomes visually apparent which routes score well both in an economic and environmental sense. Sensitivities of the results for different input parameters were also investigated.

One or more treatment routes were investigated for the following end-of-life (EoL) products: 1 ton of flat panel displays (FPDs), 1 ton of CIGS solar panels and 1 ton of energy efficient lamps (EEL). For FPDs and CIGS panels these routes are a mechanical treatment-based route, a manual dismantling-based route and a hybrid of these two. For EEL a mechanical route was investigated. Each EoL product has a benchmark route as well, in which no critical metals are recovered.

The results show that for most EoL products and processing routes, there is much more variation in the economic (internal) costs than in the environmental (external) costs. The change in environmental impacts related to the additional hydrometallurgical process steps are limited compared to the manual and/or mechanical treatment.

Using the base input parameters, the most eco-efficient treatment route for FPDs is the mechanical route, while for EEL, the Reclaim route scores the best. However, for both EoL products the difference with the benchmark route is very small. The mechanical route is also the most eco-efficient regarding the treatment of CIGS panels, except when the (manual) dismantling time is assumed to be lower (2 min.), then the manual route is preferable.
The results of the economic assessment determines in a strong way the overall picture. From that point of view more attention is given to these results:

- The only profitable routes under the current assumptions are mechanical and semi-manual processing of FPDs, as well as the benchmark processing of FPDs – without critical metals recovery. For CIGS panels, manual dismantling followed by EVA pyrolysis and recycling of the front glass, can be profitable if dismantling takes little time (2 minutes) or if carried out in the Eastern part of Europe where labour costs are lower than average.

- Energy efficient lamp recycling is not profitable, even if the full price can be obtained for yttrium and europium. This is not likely because it is very difficult to split yttrium and europium into pure metals, and the prices of these metals are under pressure from a decreasing demand as a result of increasing sales of LED lamps. Still, considering that lamps need to be processed due to their mercury content, adding recovery of rare earths from fluorescent powder to the line of processing can decrease the net costs of lamp treatment.

An important sensitivity parameter for the hydrometallurgical step is the number of times the chemicals are recycled. For all treatments, increased recycling of chemicals lowers the costs, but the effect is largest for the treatment of CIGS panels. Without recycling of chemicals, none of the routes are more eco-efficient than the benchmark routes.

In the sensitivity scenarios, the prices of several recovered materials were also varied to investigate the effect of higher or lower price levels. For FPDs, especially the price received for the recovered PCBs appears to be an important determinant of profitability, while the price received for critical metals is less important.

For CIGS the costs for the manual operation are very sensitive. Short dismantling times and operation in Eastern Europe has a strong influence on the overall costs.

When looking only at the additional hydrometallurgical treatment step to recover critical metals, it becomes clear that recycling of chemicals is a crucial determinant for the economic and environmental impact.

More specific economic consequences of the recovery of critical metals are:

- The costs to recover indium from FPDs are, for now, slightly lower per kilogram than the market price (2015). In decreasing order of contribution, the costs are installations, personnel, chemical waste disposal, heat for leaching and electricity.

- Adding recovery of europium and yttrium compounds to an existing EEL treatment route seems to be beneficial for the costs/revenues balance, but only at assumed prices (2015). If the prices for europium and yttrium were ten times lower and two times lower, respectively, the treatment would cost more than the benchmark route.

- Indium and gallium concentrations in CIGS panels are higher than in FPDs. It makes the hydrometallurgical processing more worthwhile. Compared to the benchmark treatment of CIGS panels (removing aluminium frame, size reduction and application of the panel as building material), the mechanical route with In/Ga recovery gives a real net revenue (based on 2015 prices).

Potential Impact:

1.4.1 General

The actual recycling infrastructures for WEEE are set up with the aim to recycle the bulk metals ferrous, aluminium, copper and interested engineering plastics. Moreover the more toxic metals, such as mercury,
cadmium and lead are concentrated and also valuable metals, such as gold, silver and precious metals are recycled. Till now the critical metals e.g. indium, gallium, yttrium and europium, are lost in slags, ashes and other waste residues.

Europe is considered to be a fertile ground for establishing an advanced infrastructure for the recycling of more metals from E-waste as (1) it is an important and growing market for PV, SSL and electronics, (2) there is a recognised need to extend on manufacturing technology with high added value to remain globally competitive, (3) it will contribute to become less dependent for raw materials supply from non-EU countries, (4) there is a positive attitude towards recycling and the necessary waste collection systems, and (5) there is a need for the overall reduction of waste.

With the results of the RECLAIM project it has been proven that with a balanced application of dismantling, diminution, sorting and separation techniques the critical metals can be concentrated to such a level that the implementation of a sequential hydrometallurgical step becomes challenging. With the help of dedicated leaching, extraction, and purification techniques the concentrated critical metals are gained in such a compound and/ or purity that further, advanced application in comparable products or other new products/materials becomes possible. It is technically possible to recycle metals, which are applied in rather low concentrations in PV, SSL and electronics waste.

The results of economic and environmental assessments illustrate and support the successful introduction of the designed and developed additional technical operations in a running WEEE treatment infrastructure. It is economically interesting to enlarge the actual WEEE infrastructure with central or regional hydrometallurgical activities. SMEs can be involved in the enlargement of the recycling activities. This successful technical innovation will have a positive spin-off regarding other starting technological developments in the circular economy.

For the PV, SSL and electronics industry, implementation of the results will imply a relief of the supply pressure for the considered metals, stabilise pricing and mitigate sourcing risks.

The social impact of the intensification of recycling activities for this kind of waste in Europe will bring some relief to the environmental disaster and exploitation of people under unhealthy and harsh working conditions in such regions as Guiyu (often referred to as “the E-waste capital of China” or “electronics graveyard”) and may mark the end of this intrinsically unsustainable practice. New, attractive recycling activities in Europe can reduce the exports and can lower the unemployment in several European countries. This will provide additional educational and training opportunities. It will encourage more regional recycling activities for other discarded products and waste streams. The economic, environmental and social benefit for such a more regional, circular approach will have a recognizable, positive impact on society.

1.4.2 Dissemination
Website
The RECLAIM webpage was created with the web developer tool Macromedia Dreamweaver 8 and launched in early February 2013. The actual homepage is available under the following web address: www.re-claim.eu

The webpage gives an overview about the whole FP7 project RECLAIM, including information on the workpackages as well as the involved partners. The secured area within the webpage is used to upload administration and dissemination material, completed reports and deliverables as well as information on the General Meetings (presentations, minutes, agenda etc.). SAT is managing and hosting the whole
Dissemination event ‘Green Electronics 2013’
The dissemination event ‘Green Electronics 2013’ for the FP7 project ‘ZeroWIN’ took place in Budapest
and Szentendre from November 4-6, 2013. This platform, where experts with industrial and academic
background from all over the world met each other to share knowledge, was used to give general
information about RECLAIM to interested attendees and to distribute information about the next
dissemination event, the ‘Going Green – CARE INNOVATION 2014’ in Vienna.

Dissemination event at Going Green – CARE INNOVATION 2014
A successful half day dissemination event was organized on Wednesday, November 19, 2014 in the
framework of the international conference Going Green – CARE INNOVATION 2014 in Vienna (AT). The
preparatory work started with preparing the full papers and later on also the presentations:
• Introduction to and Motivation behind the project “RECLAIM - Reclamation of Gallium, Indium and Rare-
Earth Elements from Photovoltaics, Solid-State Lighting and Electronics Waste” (Marc van Kleef, TNO)
• Characterisation and selection of feed (Alex Branderhorst, Coolrec)
• Separation Technologies for pre-treatment, disconnection and sorting (Dorleta Guarde, Indumetal
Recycling)
• Recovery of precious and critical metals from Lamps (Silvia Giorgetti, Relight)
• Recovery of Galium and Indium from Liquid Crystal Displays and CIGS Photovoltaic modules (Wil
Steegs, ONDEO)
• First plans for pilot plants (Florian Kleber, CVL)
• First results from Impact Assessment (Toon Ansems, TNO)
The dissemination event was well attended (about 50-80 persons were always present).

Dissemination event at Coolrec Belgium in Mechelen/Tisselt (2016)
Organisation of a successful RECLAIM dissemination event at Kasteel Tivoli and Coolrec Belgium in
Mechelen/Tisselt on June 2, 2016, in which the pilot lines were presented, including a visit to the
Indium/gallium pilot on site.
The event attracted around 84 persons from government, companies and universities.

Morning session: welcome, presentations and discussion:
• Welcome to the workshop by Mr. B. Kopacek (today’s moderator)
and Mr. A. Wittekoek (Coolrec)
• Introduction to RECLAIM (Ms. S. Wiegersma, TNO)
• Recovery of Yttrium and Europium from Energy Efficient Lighting (Ms. S. Sgarioto, Relight)
• Recovery of Indium and Gallium from Flat Panel Displays and Photovoltaic (CIGS) modules (mr. W.
Steeghs, Ondeo/Suez Water)
• Environmental and economics assessment (Mr. T. Ansems, TNO)
• Recognition and selective dismantling of components from Printed Wiring Boards (Mr. C. Pramerdorfer,
CVL / Mr. B. Kopacek, SAT)
• Introduction to Coolrec Belgium and the demo plant (Mr. A. Branderhorst, Coolrec)

Afternoon session: visit to the to Coolrec Belgium in Tisselt:
• Tour through Coolrec Belgium FPD-line and demonstration of pilot plant

The presentations have been uploaded to the RECLAIM website.
Dissemination event at EGG 2016 (Electronics Goes Green, Berlin, Sept. 7-9, 2016)
Electronics Goes Green 2016 (September 7-9, 2016, Berlin) conference has been used to disseminate the final results after pilot trials. In this conference we had three RECLAIM presentations:
• Environmental and Economic Assessment of Critical Metals Recovery
By: Toon Ansems, Arjan van Horssen, Stijn Dellaert, TNO, Utrecht, Netherlands
• RECLAIM Project: Recovery of Yttrium and Europium from Electronic Waste, a New Hydrometallurgical Process
By: Vicente Lopez, Carlos Alvarez, Tecnicas Reunidas, Madrid, Spain; Serena Sgarioto, Relight, Rho, Italy; Dorleta Guarde, Indumetal Recycling, Asua-Erandi, Spain
• Intelligent Disassembly of Components from Printed Circuit Boards to Enable Re-use and more Efficient Recovery of Critical Metals
Bernd Kopacek, SAT, Vienna, Austria
Other dissemination activities
In addition, presentations have been given at several other conferences, which have been reported in the plan for use and dissemination.

1.4.3 Exploitation of results
At the General Meeting in Bucharest (RO) on June 18, 2014 a successful Exploitation Strategy Seminar took place with the support of the consultant Peter Mogyorosi. The results were further developed during this period to a PUDF – Plan for Using and Disseminating the Foreground.
Main conclusions of the first RECLAIM Exploitation Workshop:
• An “integrated and flexible separation of flat panel displays and PV modules and recovery process of Indium and Gallium” has been identified as the most promising results for joint exploitation for the moment, by Ondeo, Coolrec and TNO.

• The “recovery of Yttrium and Europium from Energy Efficient Lighting” will be exploited by Tecnicas Reunidas alone. They will need additional 2 years in order to become main licensee of the technology and potential general contractor of the subsequent industrial plant.

• Another joint exploitation between CVL/CogVis and SAT/ISL might happen later on with the “identification and automated disassembly of printed circuit boards and their components” either for re-use of components or targeting the recovery of precious and critical metals. However, such exploitation is depending on available information (database) on the material content (bill of materials) and re-use value of individual components. As this does not exist yet and the online detection using LIBS is not possible, not much market potential is existing at the moment.

• Optoel will offer “LIBS technology” for (offline) identification of rare elements in samples starting approximately 6 months after project end as well as use this technology in its optic laboratory.

List of Websites:
Project website: www.re-claim.eu
1 Nederlandse Organisatie voor Toegepaste Natuurweten-schappelijk Onderzoek TNO Toon Ansems
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2 CogVis Software and Consulting GmbH Michael Brandstoetter brandstoetter@cogvis.at
3 Optoelectronica – 2001 SA Brindus Comanescu brindus@optoel.ro
5 Indumetal Recycling, S.A. Dorleta Guarde dguarde@indumetal.com
6 Relight s.r.l. Serena Sgarioto serena.sgarioto@relightitalia.com
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