LIFE Project Number
LIFE13 ENV/IT/001033

FINAL Report: Summary of the technical part
Covering the project activities from 01/06/2014 to 31/08/2017

Reporting Date
05/01/2018

LIFE+ PROJECT NAME or Acronym
PHOTOLIFE

Project Data

Project location	Italy
Project start date:	01/06/2014
Project end date:	31/08/2017
Total Project duration (in months)	39
Total budget	€ 1,284,796
Total eligible budget	€ 1,270,796
EU contribution:	€ 634,000
(%) of total costs	49.35
(%) of eligible costs	49.89

Beneficiary Data

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1. List of contents

Abbreviation:

EP	Ecopower
EC	Eco Recycling
GE	Green Engineering
HTR	High Tech Recycling Centre
PV	Photovoltaic Panels
CC	Coordination Committee
TC	Technical Committee

2. Executive Summary

Description of the project

The project aims at demonstrating an innovative process for the recovery of solar-grade glass and metals from photovoltaic panels of the following different technologies: Si-based panels, CdTe panels, and innovative panels including CIGS and CIS. The process includes the dismantling of electric equipment and frames, and the mechanical pre-treatment. The mechanical pre-treatment produces solid fractions that require different treatments. The coarse fraction is treated by solvent to separate clear glass from plastics (EVA, tedlar), the intermediate fraction is leached to eliminate metal impurities and thus obtain an additional fraction of clear glass while the fine fraction, is leached by an acid solution to recover metals.

To demonstrate the process described above, a prototype plant with a processing capacity of 200 tons of panel/y, allowing for mechanical and physical treatment was designed and constructed. The leaching of the intermediate and fine fraction obtained by mechanical pre-treatment, whereas, was performed in an already existing pilot plant owned by Eco Recycling (coordinator beneficiary) that was realized in a previous FP7 EU-programme project. During the demonstration activities, almost 3 tons of end-of-life photovoltaic panels including Si-based panels (1008 kg), Cd-Te panels (756 kg), CIGS panels (1108 kg) have been collected and processed.

Key deliverables and outputs

The project objectives can be described as follows:

a) Design and construction of the prototype composed of two sections for mechanical and physical (solvent) treatments (200 ton/y);
b) Demonstration activity including the treatment of 1008 kg of Si-based panels, 756 kg of CdTe panels and 1108 ton of CIGS panels;
c) Optimisation of the mechanical, solvent, leaching and wastewater sections in order to increase the effective of the treatment reducing both the wastes and the energy consumption;
d) Obtainment of sufficient amount of products to test merceological properties by main end-user: glasswork and cement factory.
e) Definition of mass and energy balances according to the characterization of the input waste flow and the optimised running of the process within the demonstration activity;
f) Evaluation of impact assessment of the process proposed with respect to alternative process (including thermal treatment);
g) Economic analysis of the process for large-scale plant (processing capacity 5000 t/y) in view of the waste projection in Italy and Europe (estimated in the project) and the operating take back policies and consortia in the field.

The key deliverables of the project, each of them corresponding to a report, can be summarized as follows:

a) Prototype plant design and construction (associated action: B7 and B8);
b) Disassembling, physical and mechanical treatment (associated action: B9, B10, B12);
c) Optimisation of the disassembling, physical, mechanical treatment and wastewater treatment (associated action: B9, B10, B11, B12);
d) Chemical characterization of all solids and liquids generated by the pre-treatment plant and the hydrometallurgical plant (associated action: B13). The clean glass obtained by treating spent PVP was sent to the "*Stazione sperimentale del vetro*" (Murano, Italy) for a complete analysis of the product including: chemical analysis, experimental fusion and optical microscope observation, granulometric analysis, determination of heavy mineral content (mineral analysis). The products are on evaluation by an external specialized laboratory for glasswork certification and a relevant cement factory to verify the possibility of reusing them into the two production chains as secondary raw material;

e) Verification of the mass and energy balances of the mechanical pretreatment section and chemical treatment section operated under optimized conditions (associated action: B9, B10 and B12);
f) Environmental impact assessment (associated action C1);
g) Economic analysis (associated action B14) and financial prevision for future full-scale plant (associated action: C1.3).

Progress of project actions

Targeted objectives have been achieved in the following main activities:

- analysis of existing data including a market analysis and a preliminary assessment of the process balances (actions B1-B3);
- retrieval and characterization of panels (actions B4-B5);
- process and plant design (actions B6-B7);
- prototype construction (action B8);
- process demonstration by prototype operation (actions B9-B13);
- economic analysis (action B14);
- lab-scale tests (action B15);
- monitoring environmental and socio-economic impact (actions C1-C2);
- dissemination of project results (actions D1-D2);
- management (actions E1-E5).

The project was completed according to the foreseen scheduling and despite some deviations that did not, however, affect the target achievement in due time.
In particular, from the technical point of view, the main target was the prototype construction which has been completed both for the solvent treatment section and the mechanical pre-treatment section. Regarding the crushing unit, commissioned tests at the beginning showed the most suitable technologies to meet the process' objectives. Based on the evaluation of the samples from these external campaigns, pre-mechanical units have been designed and built specifically for the PV applications. The samples from the external campaigns has been used in the first solvent treatment tests. After the Photolife mechanical section was installed, the materials from the mechanical section has been used to feed the physical section unit for the solvent treatment demonstration activity.

Preliminary solvent treatment tests performed on crushed material on lab scale confirmed the capacity of the process to give high purity solar glass. After the first prototype tests occurred, the output glass obtained were evaluated from the "*Stazione sperimentale del vetro di Murano*" an institution authorized to operate as a Notified Laboratory at the European Commission for certification of glass products and involved with the technical and scientific problems of the entire glass industry.

Other main activities concerning the project's technical aspects are the panel retrieval and the authorization procedure. Regarding the first aspect about 1008 Kg of Si-based panels, 1108 kg of CIGS innovative panels and 756 Kg of CdTe panels have been collected and classified. The target collection has been fulfilling for the Si-based and CIGS category. Despite the efforts to retrieval 1 ton of CdTe PV type, the collected amount is just below the target. The difficulty in finding this type of panels is due to the common practice of the suppliers to sign contracts with the end-users to uninstall themselves the panels at the end of life. These panels are classified as "hazardous waste" because of the presence of cadmium and are currently sent to existing plants that performs specific treatments for the CdTe ones. It's an example the "First Solar process" that was developed by the United States company "First Solar" (the European headquarters is in Germany) for the recycling of cadmium telluride modules. To prevent any problems related to the disposal of cadmium, the company has decided to deal with both production and disposal of its modules. The process foreseen

a strong mechanical treatment following by a very aggressive acid leaching, a mechanical separation to recover glass and finally a precipitation step to obtain a metal concentrate.
The demonstration activity using CdTe PV on prototype was however considered sufficient to define the most suitable process conditions for their treatment.
As for authorization, the procedure was clarified from a formal point of view and an integration to the existing authorization for treating WEEE owned by Eco Recycling was implemented.
All details about slight deviation and new ending date of each action are detailed as follow.
As a general observation, small delays (few months) of some actions during the project have not affected the achievement of the project's targets within the end of the project (August 2017).
Even from an economic point of view the project was running accordingly to the initial plan: almost 96% of the total budget costs were met.
The activity of each action in the project can be summarized as follows:

- **Action B1 - Analysis of HTR lab results**
  Mass and energy balances were derived for the proposed process based on the results of lab-scale research activities performed prior project starting. Expected results defined in the original project description were attained. In particular, two reports were elaborated (one for Si-based panels and one for CdTe panels) including the process scheme, mass and energy balances for the proposed process and an alternative recycling process relying on the thermal treatment of panels.
- **Action B2 - Estimation of the market trend**
  A detailed analysis of the amount of photovoltaic panels installed at EU level was performed. The analysis included the quantification of panels installed during the past two decades and prediction of panels that will be installed during the following years. Information about the market share of the different technologies was included. Collected data were employed to predict the future fluxes of end-of-life panels. The composition of the panels was used to derive information about the fluxes of secondary raw materials that can be recovered. The action was completed, and a report was elaborated including the results of the study.
- **Action B3 - Preliminary economic feasibility**
  The economic feasibility of the proposed process was assessed by recourse to mass and energy balances derived from lab-scale experimental results. Process simulations were performed evidencing that the processing capacity required to ensure economic feasibility of the proposed process is in line with the future fluxes of end-of-life panels that will be generated at national level. The action was completed in line with the original project description.
- **Action B4 - Photovoltaic panels retrieval and classification**
  45 Si-based panels plus 55 Kg of Si-based grinded panels, 63 units of CdTe and 60 units of innovative ones were collected and classified. The online database has been progressively updated. The collecting target has been reached for Si based panels (1008 kg has been collected) and for the innovative ones (1108 kg of panels collected). For the CdTe type, the collected amount is just below the target (756 kg of panels already collected). This activity was extended until the end of July 2017.
- **Action B5 - Retrieved panel characterization**
  The procedures for the chemical characterization of the collected panels were optimized. A delay was accumulated owing to the difficulties encountered in the collection of panels (action B4). Therefore, this activity was extended until the end of July 2017.
- **Action B6 - Process design**
  A detailed flowsheet including flow-rate and composition of any stream was performed. The plant units required to perform the process were identified and the sizing of the main plant units was completed. Achieved results are in line with the expectations reported in the project description. A report was elaborated including a description of the performed activities.
- **Action B7 - Pilot plant design (including offer request)**

Detailed plant design was completed in line with the original project description and both for the physical treatment section (solvent treatment) and the mechanical pretreatment section.
A report was elaborated including detailed design specification of the plant's units. This activity was extended until the end of June 2017 due to small delays in the mechanical section design activity that however have not affected the achievement of the project targets.

- **Action B8 - Pilot plant construction**
  The construction of both the physical and mechanical treatment sections was completed. The solvent treatment unit and the mechanical unit are entirely installed into two different containers that were transported to the industrial site of the Eco Recycling srl (EC), in Civita Castellana (Viterbo, Italy). A delay related to partnerships issues, was accumulated during the construction of the solvent treatment section. Eco Recycling take on the purchase of both sections in order to realize the whole prototype.
  The request for authorization integration was presented: the Photolife plant is (in accordance with Regional Rules) an integration of the already existing and already authorised plants of Eco Recycling. Accordingly, the Region accepted a simple application form for the integration of already existing authorized plant.
  This activity was extended until the end of June 2017.
- **Action B9 - Disassembling and physical treatment**
  In this action, the silicon based and CdTe panels retrieved within the action B4 have been processed. Dismantling of all panels was realized with different techniques. Mechanical pre-treatment tests were conducted using industrial shredders (made available by candidate suppliers) first and the Photolife unit later. The coarse fraction produced by the mechanical section was then treated in the solvent treatment unit. The action was extended until July 2017. A report was elaborated including a description of the performed activities.
- **Action B10 - Chemical treatment**
  The intermediate and the fine fractions was chemically treated in order to recover minute clean glass in the first case and a metal concentrate in the second one. The action was extended until July 2017. A report was elaborated including a description of the performed activities.
- **Action B11 - Wastewater treatment: optimization**
  Within this action, the wastewater from the solvent and chemical treatments were analyzed and finally treated by GSA srl, a company specialized in the wastewater treatment located close to the Eco Recycling site in Civita Castellana. The solvent recovery was performed in order to reduce the process losses. In accordance with end of the actions on the prototype, this activity ended in July 2017.
- **Action B12 - Experiments using innovative photovoltaic panels**
  A prototype experimentation was conducted on the innovative CIGS (copper indium gallium selenide) panels. An initial delay in the activity was due to a delay in the plant construction. This action was concluded on July 2017.
- **Action B13 - Product Characterization**
  The products obtained by the mechanical and chemical treatments were characterized. In accordance with the end date for the actions B19, B10 and B12, this activity was also extended until July 2017.
- **Action B14 - Economic analysis and management strategies**
  Implementation of material and energy balances obtained by the pilot plant tests have been used to simulate the Photolife process using both a specific simulation software and calculate sheets property of Eco Recycling. The flux of material and possible revenues during next years have been evaluated for the use of the realized pilot plant with a potentiality of 200 ton/year.
  This whole action ended at the end of the project on August 2017.
- **Action B15 Lab scale treatment of innovative photovoltaic panels**

Different types of CIGS panels were treated. Solyndra, which is a specific type of CIGS panels present tubular shape with three concentric tubes filled with silicon oils. Solibro is flat type panel, which were crushed by the mechanical treatment and directly submitted to physical and chemical treatment. By this way copper, indium, gallium and selenium can be extracted in liquid phase for possible exploitation while glass is cleaned for recycling. This activity was extended until May 2017.

- **Action C1 Environmental assessment of the project impact**

  In the sub-action C1.1 (Monitoring the environmental impact of the pilot plant activities during the project), a preliminary analysis was performed to identify within the constructed plant the main sources of pollutants; during the operative phase on the prototype, the acoustic emissions, the powder released in the atmosphere during the mechanical pretreatment, the vapors released during the treatment with solvents and the metals present in the wastewater were monitored. A life cycle assessment was realized in sub-action C1.2 including: statement of the goal and scope of the LCA, Life Cycle Inventory Analysis based on the material and energy balances preliminary data first and on pilot plant data later. In the first case the environmental impact of the Photolife process and the landfill disposal was compared. In the second analysis a comparison of the Photolife and thermal processes was carried out.

  Sub-action C1.3 started with a basic economic feasibility analysis for three production cycles with different treatment capacities; then, data has been updated with test results and a business plan for a 5000 t/h plant capacity was realized.

  This whole action ended at the end of the project on August 2017.

- **Action C2 Assessment of socio-economic impacts**

  The socio-economic impact of the prototype has been analyzed: the possibility to treat other types of WEEE in the prototype and the social repercussions of the innovative pilot plant have been evaluated. This action ended on august 2017

- **Action D1-D2 Dissemination**

  In action D1 achieved results were:

  1. The link to the project website in the Facebook page of Eco Recycling;
  2. Completion of a target groups mailing list for future dispatches;
  3. Project brochures (500) printed and distributed;
  4. Five Press release by the magazine HIGH Tech Ambiente and Campo de' Fiori, University of L'Aquila and HA PARTS & COMPONENTS;
  5. Website periodic updates with the lasts news, photo galleries and events;
  6. Presentation of the project at 5 congresses;
  7. Four presentations to interested groups and stakeholders: Confindustria Chieti, GA Energy SpA, Apliquim Brasil Recicle, NIKE srl;
  8. Visits on demand (GA Energy SpA, Apliquim Brasil Recicle company);
  9. 3 papers on scientific journals (1 submitted, 2 released) and 2 proceeding of conferences
  10. Open day
  11. Final conference
  12. Meeting with the Ministry of the Environment

  In action D2 more specifically expected results already obtained for this action are: Notice Board set in the industrial site of EC (Deliverable D); plate at entrance of HTR (High Tech Recycling Centre), EC and EP; project web site and layman's report.

- **Action E1-E5 Project management**

  Difficulties were encountered which imposed to revise the repartition of activities among partners whit an improved Partnership Agreement.

  Some difficulties were encountered in the purchase of the shredder unit, which imposed a delay in the construction of the mechanical pre-treatment section. However, the physical treatment unit was considered fundamental both for the completeness of the prototype and to realize a specific unit for the treatment of a material consisting mainly of glass that therefore requires an ad hoc shredding technology. It was considered important to carry out at the beginning testing campaigns using several industrial grinding machines. This allowed to define the most suitable shredding technology for the PV panels (in particular, a single-shaft shredder was chosen). Such shredding technology has been optimized and designed to minimize the production of powders.

3. Introduction

Environmental problem addressed

PV industry has been rapidly growing over the past decade. Europe has grown from an annual market of less than 1 GW in 2003 to a cumulative PV capacity of 104 GW in 2016 and a 34% share. In accordance with these data, approximately the flux of end-of life panels will reach 500,000 tons/year within the following 20 years. Besides preventing detrimental environmental effects (dispersion of heavy metals), the recycle of the end of life panels can be exploited to recover valuable raw materials. Since 2012, end-of life panels are included in the EU WEEE Directive, which regulates the treatment of waste electrical and electronic equipment and requires the collection and recycling by manufacturers and importers. PHOTOLIFE proposes a full recovery of end of life photovoltaic panels of different types (crystalline Si, amorphous Si and CdTe and CIGS).

Hypothesis to be demonstrated / verified by the project

The main assumptions that have been demonstrated during the project can be summarized as follows:

- The process can be implemented to recycle panels with different technical characteristics (crystalline Si, amorphous Si and CdTe and CIGS);
- The constructed prototype plant will allow sustaining a processing capacity of 200 tons of panels/y;
- The process will allow recovering an amount of glass larger than 80% of the panel weight;
- A concentrate of metals covering about 2% of the panel weight can be generated by hydrometallurgical treatment of this fraction that is obtained by mechanical pre-treatment;
- Economic feasibility of the proposed process at industrial scale.

Expected results and environmental benefits

The main targets of project have been followed in order to demonstrate the technology and validate the process at a pilot scale.

Main expected results can be summarized as follows:

- Process of 3 tons of panels including 1 ton of Si-based panels, 1 ton of CdTe panels and 1 ton of innovative panels.

  Reached results: Silicon-based technologies have been collected more easily since it is the technology most abundant on the market (1008 kg collected, +0,8% of the target); even the innovative panels, CIGS technology, has been totally collected (1108 kg collected, +10,8% of the target). The CdTe panels have been quite difficult to recover as they belong to the dangerous electrical and hazardous waste category; for this reason, they are often retrieval directly from the suppliers and started for specific hazardous waste disposal. The amount of collected CdTe panels is slightly lower than the project target; this has not prevented comprehensive experimental tests on this PV type to be done (756 kg collected, -24,4% of the target). In the table 1 below, the amount of materials which were treat in the prototype plant is shown:

Tab.1: kg of materials which were treat in the prototype

Treatment	Si-based	CdTe	CIGS	Tot
Mechanical	1008	756	1044	2808
Physical (solvent)	637	469	623	1729
Chemical (hydrometallurgical)	255	261	365	881

The tests were carried out separately for the different panel categories. It has not been considered advantageous to test a mix of the various types due to the following factors: 1) the different amount of panels for each type present on the market; in fact Si-based panels are the most abundant followed by the CdTe which furthermore have a dedicated disposal as hazardous wastes while CIGS are innovative panels and therefore less abundant; 2) the great heterogeneity of the compositions, which also results in a different classification of the panels (eg CdTe are classified as dangerous while Silicon and CIGS are not); 3) the different process yields for the two categories: clean glass obtain from the Si-based panels is more transparent and therefore more valuable than the CdTe. Based on these considerations, it was accounted more effective to test separate campaigns.

- Recovery of 800 kg of glass from each ton processed panels.
  Reached results: the average percentage of glass recovered by treating the collected panels is approximately 72,5% of the panels processed, this percentage has been fixed after the experimentation activity. The amount of clean glass recovered from each category of panels are reported in the table (Tab.2) below:

Tab.2: Kg of glass recovered within the Photolife project

	Si-based	CdTe	CIGS	Tot
Coarse glass	510	413	548	1471
Intermediate glass	175	196	194	565
Total	685	609	743	2037

- Production of metallic concentrates.
  Reached results: 1) 0,43 kg of Al and Zn based metallic concentrate and 72,2 kg of solid residue reach in TiO2 and Ag from Si-based panels treatment 2) about 0,09 kg of Al, Zn, Te based metallic concentrate from CdTe panels treatment 3) 0,24 kg of Cu, In, Ga, Cd, Zn, Mo based metallic concentrate from CIGS panels.
- Development of a procedure for the treatment of wastewater (about 2000 L for each type of panel).
  Reached results: Procedures for the treatment of process liquid waste (leaching water, solvent-contaminated water and solvents with dissolved and suspended plastics) have been defined. Total wastewater amount to be treat were lower than expected: 1) the solvent was recovered and reused in the plant; 2) the wastewater resulting from physical treatment has been reused in the process (only small purges were necessary: about 1 cubic meter of wastewater from this treatment have been collected); 3) the water resulting from the chemical treatment has also been reused in several cycles before being disposed (the wastewater collected in leaching treatments have been: 750 L for Si-based panels treatment, 680 L for CdTe panels treatment and 490 L for CIGS treatment).
- Reduction of the greenhouse gas emissions compared to alternative recycling processes that include thermal treatment of panels.
  Reached results: it has been widely demonstrated that glass obtained from recycling processes is more sustainable from an environmental and economic point of view respect of the raw materials extracted from primary ores. However, it is not easily to assess the advantage of using the Photolife hydrometallurgical process compared to a thermal process. For this reason, an LCA was implemented to compare the two processes.
  In particular, the LCA permitted to define the greenhouse gas emissions of the Photolife process. Comparing the project results to the thermal treatment of PV, the emission related to the process developed in the Photolife Project resulted lower than the thermal one (Deliverable C1).

Description of the technical / methodological solution
Targeted objectives have been attained by the following main activities: analysis of existing data including a market analysis and a preliminary assessment of the process balances (actions B1-B3);

retrieval and characterization of panels (actions B4-B5); process and plant design (actions B6-B7); prototype construction (action B8); process demonstration by prototype operation (actions B9-B13); economic analysis (action B14); lab-scale tests (action B15); monitoring and assessing environmental and socio-economic impact (actions C1-C2); dissemination of project results (actions D1-D2); management (actions E1-E5).

Expected longer-term results

The demonstration of the proposed process at full industrial scale is the main result to be achieved within the five years that will follow the end of the project.

Having demonstrated both technical and economic feasibility under this project, a stakeholder commissioned Eco Recycling to design a full-scale industrial plant capable of handling 5000 t/y of end-of-life panels via the same treatment defined in the Photolife project.

The commitment of the partners has also been aimed at stimulating local authorities to produce a specific legislation for photovoltaic panels disposal that are now treated like the other WEEE in the same category (Meeting with the Environmental Minister). In addition, the process developed in Photolife meets the limits imposed by European legislation (Directive 2012/19 / EU), which provides for specific recovery rates (80%) and recycling (70%). The recycling and recovery rate reached in the Photolife project is shown in the Tab.3:

Tab.3: Recovery and recycling percentage rate within the Photolife project

	Si-based	CdTe	CIGS
Aluminum	10	0	0
Glass (coarse+intermediate fraction)	68.7	79.9	74.2
Metallic contacts	0.7	1.7	1.1
Fine residual to cement factory	7.1	8.0	15.6
Total	86.5	89.6	90.9

Based on the considerations already made and in view of the expected quantities of wastes in Europe, it would be advantageous to foreseen in Europe full-scale plants located where the amount of PV wastes will be remarkable.

4. Administrative part

4.1 Description of the management system

Project manager takes care of the financial and administrative management of the project activities including organization of kick of meeting, the collection of all administrative and financial documents and monitoring of technical results according to project scheduling.

The Technical Committee coordinated the execution of technical activities in completed all the project actions and took care of mandatory and general dissemination activities.

The main project phases, all the project activities and tasks are shown in the following table (Tab.4):

Tab.4: Project Actions

Elaboration of existing data
B1 Analysis of HTR lab results
B2 Estimation of the market trend
B3 Preliminary economic feasibility
Photovoltaic panels retrieval and characterization
B4 Photovoltaic panels retrieval and classification
B5 Retrieved panel characterization
Process and plant design and realization

B6 Process design
B7 Pilot plant design (including offer request)
B8 Pilot plant construction (including site preparation and authorization request)
Pilot plant experiments
B9 Disassembling and physical treatment: optimization using Si- and CdTe-based panels
B10 Chemical treatment: optimization using Si- and CdTe-based panels
B11 Wastewater treatment: optimization
B12 Experiments using innovative photovoltaic panels
B13 Product Characterization
Economic analysis
B14 Economic analysis and management strategies
Lab scale tests with innovative photovoltaic panels (CIS and CIGS)
B15 Physical pre-treatment and chemical treatment of innovative photovoltaic panels
Monitoring phase
C1 Environmental assessment of the project impact
C1.1 Monitoring of environmental impact
C1.2 LCA
C1.3 Preliminary environmental impact assessment and financial prevision for future full-scale plant
C2. Assessment of socio-economic impacts
Dissemination phase
Management phase

The original project planning was modified to deal with various kinds of problems that occurred during the project. The new scheduling of the actions is reported in the Gannt chart (par 5.1), where the black line indicates the beginning of the additional months necessary for actions conclusions. Considering also the buffering time foreseen during the project writing, no delay in completing the project affected to reach the targets in due time. In order to carry out all the activities foreseen, the planned time for some actions has been extended, remaining anyway by the end date of the project.

In order to complete the project in time and according to the actions envisaged, it was necessary, as suggested by the EU a “strong management action” that entailed the temporary insertion of new staff to assist the management of the project itself as well as the execution of the actions.

The project actions have been closely monitored during the project. Each action was accompanied by specific indicators which were reported in the project description and whose achievements have been monitored during the CC meetings.
In addition to the monitoring of reaching the actions’ objectives, the respect of time scheduling and the proper execution of the actions has been gradually supervised.
All the results of these monitoring actions were assessed during the management meetings.
The overall results of the monitoring activities have been reported to the Commission in the inception report, the mid-term report and in this final report.
Main results of management were:

- Formal and informal (Skype call) meetings of the Coordination Committee;
- Deliverables submitted in due time;
- Periodic evaluations of the progress indicators

Progress Indicators define the project status as illustrated in technical actions in the project description:

- Environmental indicators: waste collection and treatment authorizations; compliance with gaseous emission regulation (low pollutant emissions); compliance with safety regulations;
- Financial indicators: timesheets, invoices and salary slips (collected monthly);
- Fulfillment of all duties mentioned in the Common Provisions;
- Signature of partnership agreements;
- Completion of inception report;

- Mid-term report with payment request;
- Improved partnership agreement;
- Completion of the project;
- Final report with payment request;
- Project's progress and quality: according to the established timetable and task division and obtaining the expected results;
- Financial administration: Audited accountings (for the final report).

The formal project meetings organized by Project Coordinator were as follows: kick of meeting on 24/06/2014, several skype calls and meetings with all partners to check the progress of the project's activities.
The monitoring visits with the Monitor were made on: 29/10/2014, 11/01/2016, 27-28/02/2017.

4.2 Evaluation of the management system

During the development of the project activities many problems (technical, economic, logistics and regarding authorization) occurred. All these problems are described below.

Economic issues
The EP company (EP) has not been able (for financial difficulties and internal organization) to comply with the payment terms of the plants attributed to it at the beginning.
In order to allow the achievement of project objectives, EC agreed with EP and with the other partners to substitute EP with the purchase of the part of the prototype initially attributed to EP. Partners also agreed to allocate to EP certain activities initially pertaining to EC. Even another project partner, the GE company had difficulties that prevented it to design and built the grinding section. Therefore, the company ended its activities on the prototype with the simple construction of the dedicated container. EC agreed with partners to take on the mechanical prototype pre-treatment section realization instead of GE and to allocate to GE some activities initially pertaining to EC. HTR has been available to perform some additional tasks not initially foreseen in accordance with the other partners.
It was emphasized to all partners that regardless of the internal redistribution of activities and costs, the only truly effective contract remains the one initially subscribed to the EU and which concerns total project actions and costs. The new distribution is merely a different distribution of 'actions' (and related costs) between partners.
Tanks to these changes the project objectives were achieved in due time.

Technical issues
The pilot plant design action related to the mechanical pre-treatment section, required a longer time than the initial one expected due to the redistribution of the actions between the partners. However, the technology built has given positive feedback.
Concerning the physic section (solvent treatment) after the first step of the demonstration activity, the reactor was subjected to technical adjustments that improved its performance.
The design of the mechanical pre-treatment section presented problems mainly related to the identification of the most suitable grinding system for PVP. The panel's structure mainly based on glass and the need to produce a coarse granulometric fraction to allow the reuse of the clean glass in glassworks, have been two aspects difficult to reconcile in standard industrial machines.
In the first phase of the project different technologies have been tested to examine which of them best suits the treatment of different types of photovoltaic panel. In particular the following equipment were tested: four-shaft shredder (ITS, Milan), single-shaft shredder and hammer shredder (Guidetti, Ferrara), four-shaft + two-shaft shredder system (NIKE, Albano).
Once all these data have been collected using the various available equipment at specialized companies, it was defined the best technology. Based on this technology, it has been improved and optimized for photovoltaic panels in specific way. Some parameters have been set as the control grid sizes, sieves size, size distribution of output fractions, the shaft rotation speed to optimize the

equipment performance and also to ensure that the mechanical treatment unit was versatile to process different type of photovoltaic modules.

Nature and logistical issues of authorization

At the beginning of the project, GE planned to make the mechanical pre-treatment section at a site in Termoli (Molise, Italy), and was awaiting authorization for panels storage, and for the mechanical and physical processes. The delay in the permits made it impractical. It was then decided to locate the prototype at the EC platform at Civita Castellana (Viterbo, Italy). In fact, a permission for the treatment of WEEE in hydrometallurgical experimental plant has been yet released to EC by the authority Regione Lazio. This authorization refers to a pilot plant placed in a container, able to perform chemical treatments on pre-treated WEEE. To fulfil its regional obligations and operate the pant EC has signed a guarantee policy.

Since the new prototype Photolife also processed electric and electronic components it was considered possible to relate this new activity with the already authorized one. In fact, the Photolife pilot plant has been considered (in accordance with Regional Rules) an integration of the existing plants. On this base, the Region accepted a simple application form for the integration of already existing authorized plant with the new prototype built in the Photolife project. Finally, the guarantee already signed by EC has covered the Photolife prototype activities too.

The containers (the one realized in a previous FP7 Project "HydroWEEE" and the two containers containing the Photolife prototype) was in the same platform in Civita Castellana and was integrated for wastes service and utilities.

Communication with the Commission and Monitoring team

During the project numerous informal contacts with the Monitoring Team occurred to submit managerial and technical choices made during the project to the team. This constant monitoring proved extremely useful for the success of the actions' accomplishment. Furthermore, formal meeting has been performed.

Frequent phone and email meetings were held with the monitor Dr. Rosa Clot, meeting helpful for the correct addressing of the project.

5. Technical part

5.1 Technical progress, per task

HTR researchers in collaboration with Eco Recycling developed an integrated mechanical-chemical process for the treatment of Si-based, Cd-Te and CIGS panels. Experimental tests have been performed first at laboratory scale requiring a validation by a demonstration activity in pilot scale. According to this scenario the Photolife project aimed to the design and construction of a prototype for the mechanical treatment of different type of panels and the physical treatment of the coarse fraction. In particular a solvent treatment was implemented on the coarse fraction in order to disaggregate panel multilayers. Different chemical treatments were employed for intermediate fraction and for fine fraction cleaning: a leaching solution was adopted in order to clean the intermediate fractions thus increasing the glass recovery yield and to process fine fraction to obtain a metallic concentrate. The leaching treatment of the intermediate and fine fractions was performed inside a mobile pilot plant located in the industrial site of Eco Recycling in Civita Castellana already built in an FP7 European project, "HydroWEEE Project".

Demonstration activity included retrieval of at least 1 ton for three different types of panels (Si-based, CdTe, innovative types), characterization of retrieved panels and optimization of mechanical and chemical treatment in the prototype. This goal has been reached and exceeded for two classes of panels: the silicon-based one, that are the most abundant in the market, and the innovative CIGS technology, that have been completely collected although they are still not abundant in the market (this fact also contributed to the need to increase the planned time for Action B4). However, for the CdTe type, despite the efforts in the collection phase, they have been retrieved 756 Kg of panels. The difficulty in collecting this category was not caused by its low application, but rather because very often the same vendors also attend to the withdrawal and disposal of the panels at the end of life. This practice is due to the fact that this type of panel, unlike the silicon based and the CIGS ones, falls into the category of “hazardous waste” and are currently sent to specific waste disposal facilities for this type of waste. However, it was considered that the amount of CdTe panels collected within the project did allow an exhaustive demonstration campaign to take place. The difficult in finding CdTe panels and the delay in the authorisation procedure of GE site initially (where the mechanical pre-treatment section would have to be placed at the beginning) have contributed to increasing the delay in Action B4.

After collection of sufficient amounts of innovative types of panels (CIGS) lab scale tests and also pilot scale validation were performed.
According to the scheduling of activities described in the project some delay was occurred especially concerning the construction of both the sections of the prototype. As a consequence, all actions in cascade undergo some delay. Occurred delay was mainly due to:

- Economic issues
- Technical issues
- Nature and logistical issues of authorization procedure

as it regards mainly the phases of plant construction and start-up tests on prototype (details are reported in section 4.2 of this report). Nevertheless, the project actions were completed confirming the expected results on the efficiency and effectiveness of the proposed process.
The new scheduling of the actions is reported in the Gannt chart below (Fig. 3), where the black lines indicate the end of the actions’ time scheduling at the beginning.

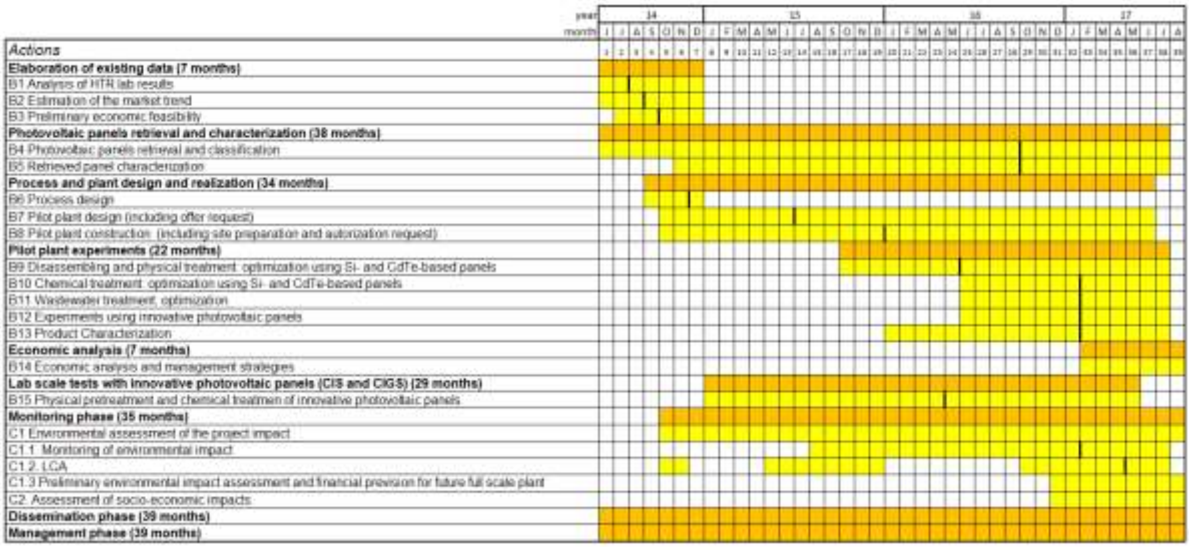

Fig.3: Gannt chart

5.1.1 Action B1 Analysis of HTR lab results

This activity has been already completed in the period 1st June-31 December 2014, starting date 1st June 2014. The deliverable was completed, all expected results produced and milestone B1 achieved (Deliverable B1). This activity was conducted by Eco Recycling.
Status: 100% complete.
This activity included the mathematical formalization of the experimental results (obtained in previous lab scale campaigns by HTR researchers) in the form of energy and mass balances for PV panel treatment according to two process schemes (thermal treatment vs. solvent treatment for EVA

disruption and panel opening). In particular, according to the expected results, two reports were elaborated (one for Si-based panels and one for CdTe panels) including the process scheme, mass and energy balances for both process options. Main emerged conclusion was that solvent treatment gave final glass recovery yields similar to thermal treatment with lower energy consumption and higher glass quality. Despite these advantages a residue of backsheets (generally TEDLAR) and gluing polymers (mainly EVA) emerged at the end of the treatment. Demonstration activities allowed the characterization of such heterogeneous wastes and the evaluation of possible reuse (Tedlar backsheets can be completely recycled while the purity of EVA determines the final possible reuse of such fraction).

5.1.2 Action B2 Estimation of the market trend

This activity has been already completed in the period 1st June-31 December 2014, starting date 1st June 2014. The deliverable was completed, all expected results produced and milestone B2 achieved (Deliverable B2). The action has been completed by Eco Recycling with the collaboration of Eco Power and Green Engineering.
Status: 100% complete.
During this activity different input data concerning PV installation in EU were collected: historical data, installed power forecast, market share of different typologies, life time of PV devices, and typical material composition of the different types. Collected data were employed to estimate the fluxes of wastes resulting from the disposal of end-of-life photovoltaic panels during the period 2025-2045. The analysis of the evolution of market share among different technologies allowed determining the amount of wastes generated by the disposal of different technologies. The fluxes of raw materials that can be recovered from end-of-life panels were also computed. Based on these latter data, the maximum income that can be obtained by integral recycle of any panel was computed.
This activity gave interesting results in view of establishing the fluxes of waste materials circulating at national levels during next years thus allowing the implementation of management strategy and the sizing of future installations for their treatment. In particular historical data put in evidence the dramatic increase of PV installation in 2011 in Italy due to government incentives, but such peak was not maintained during successive years. Accordingly, a big amount of wastes should be expected since 2030. More specifically adopting a Weibull probability function for life time of panels installed in 2011 it emerged that the amount of wastes to be treated in Italy is below 400.000 ton/year even in the period 2030-2055. This can be considered the target value for future management strategies of this waste.

5.1.3 Action B3 Preliminary economic feasibility

This activity has been already complete in the period 1st July-31 December 2014; starting date: 1st July 2014. The deliverable was completed, all expected results produced and milestone B3 achieved (Deliverable B3). The action was implemented by Eco Recycling.
Status: 100% complete.
During this activity mass and energy balances from activity B1 were used as input data to have a preliminary economic analysis of the Photolife process for the separated treatment of Si-based panels and CdTe panels or for their simultaneous treatment (two distinct reports were elaborated for these two options). Process simulations were performed by dedicated commercial software for the maximum potentiality of the prototype (200 ton/y) and for larger capability in accordance with future waste fluxes estimated in B2 activity.
Main conclusion of this report is that for prototype potentiality the Photolife process is not economically sustainable. Nevertheless, commercial exploitation of prototype products is out of the aims of Photolife project. From this preliminary study the proposed process becomes economically feasible starting from 75.000 ton/y for Si-based panels while larger potentiality (>200.000 ton/y) are necessary if only CdTe are fed in the plant. These results are encouraging for two reasons. The first reason is that developing a unique process route for all type of panels seems to be the only way in

order to treat CdTe panels less diffuse to national level. The second reason is that this preliminary economic estimate put in evidence that the potentiality necessary for making feasible the Photolife process is in agree with future national scenarios. Then two or three plants with potentiality ranging from 100.000 to 200.000 ton/y could be sufficient to solve the problem of PV waste in the future.

5.1.4 Action B4 Photovoltaic panels retrieval and classification

This activity has been already completed in the period 1st June 2014-30 July 2017; starting date: 1st June 2014. The action had a significant delay in its conclusion respect to the ending date (January 2017) reported in previous Gannt. The deliverable was completed, and the main expected results have been reached (Deliverable B4). The action was performed by Eco Power and Green Engineering.
Status: 96% complete (about 250 kg of CdTe are missing. The target in collecting was set at 1 ton of CdTe type but only 756 Kg have been retrieved and classified).
During this activity EcoPower has collected end of life photovoltaic panels, populated the online database with all information regarding the collected panels (number of modules, typology, brand, model, weight, photographs, chemical composition), and uploaded it periodically.
After the classification phase, some panels fragments have been provided to HTR to perform the merceological and chemical characterization of input wastes.
The database of panels retrieval has not reached the target scheduled at the beginning phase of the project. Later the delay in retrieval panels was caused by the difficulties in finding CIGS panels and CdTe panels.
The retrieval action was carried out by Ecopower first and Green Engineering later.
Expected results at the project beginning for collection were 1 ton for Si-based panels, 1 ton for CdTe panels, and 1 ton for innovative types. Collected panels at the end of the project were: 45 Silicon based panels for a total weight of 1008 kg, 60 innovative CIGS panels for a total weight of 1108 kg and 63 Cd-Te panels with a total weight of 756 kg.
The project retrieval target of 1000 kg has been reached and exceeded for Silicon (+ 8 kg) and CIGS (+108 kg) based panels. Despite the efforts to find CdTe panels it has not been possible to reach the target because those panels have been quite difficult to retrieval as they belong to the hazardous waste category. For this reason, the spent panels are often retrieval directly from the suppliers who are committed to customers at the moment of delivering for their specific hazardous waste disposal. However, the amount of collected CdTe panels is slightly lower than the project target; this has not prevented comprehensive experimental tests on this PV type to be done.

5.1.5 Action B5 Retrieved panel characterization

This activity has been already completed in the period 1st November 2014-30 July 2017; starting date: 1st November 2014. This action was extended respect to the first Gannt of 10 months caused mainly by the initially difficulties in retrieve innovative and CdTe panels. The action was implemented by HTR and all main results are reported in the Deliverable B5.
Status: 100% complete.
In particular, within this activity a picture in terms of materials (aluminum frame, glass, metallic contacts, electric equipment, plastic materials) and chemical composition (Fe, Al, Cu, Zn, Ti, Ag, Cd, Te, In, Ga, Se) of the wastes that were treated in the demonstration action elaborated. This characterization was performed then in strict relation with the collection of panels to be treated.
During this action the procedures for material composition and for chemical characterization have been optimized according to the intrinsic characteristics of photovoltaic wastes. It was chosen performing manual dismantling of panels for electronic equipment and aluminum frame recovery and weight. Then for the determination of the amount of glass, plastic materials, metallic contacts the same procedure which is at the base of the Photolife process was used, then detachment of the different layers by solvent. For the chemical characterization fragments of the multilayered panels were finely grinded and then digested by acid.

Considering the state of the collection a proportional number of sample of panels of the different type have been characterized in order to have a representative picture of waste input. More specifically, 10 different panels of Si type were analyzed. As for CdTe being First solar (FS380-FS382) the most abundant in the collection, we manage to characterize 6 different panels in this specific type, plus other four samples of different models. As for innovative type we have six Mia Solé panels characterized plus other four samples of two different models (Solyndra and Solibro). By this way, we could obtain results for this action including the characterization of 10 representative subsamples from 10 different panels of the 3 different types.
Performed tests confirmed that glass is the main component of panels followed by aluminum, when external frame is present. The composition for the different type of panels resulted as follow: glass 75-90%, plastic materials 7-13%, metallic contacts 1-2%, frame + electric components 1-10%. Metals present in panel multilayer structure are iron and aluminum for all panels; silver, zinc, copper and titanium for Si-based panels and cadmium and tellurium for CdTe panels. In CIGS copper, indium and gallium were found according to their composition.

On the other hand, the analysis of metallic components, mainly present in the photovoltaic cell, allows to evaluate which metals are present and in which concentrations. Thus, it is possible to understand the feasibility of recovering certain metals present at interesting concentrations, as in the case of Cd, Te, Ag, In and Se for example. In particular the metal content for the different type of panels are as follow (mg/g): Zn 5-350, Ag ~75, Ti ~190, Fe 190-400, Sn ~410, Cu 80-2500, Al 770-3800, Te ~380, Cd 20-370, Ga ~100, In ~280, Mo ~790, Se ~1480.

5.1.6 Action B6 Process design

This activity has been completed in the period 14 September 2014-31 December 2014; starting date: 1 September 2014. It has been completed on December 2014 with only one month of delay respect to the beginning Gannt and all expected results have been produced (Deliverable B6). This action was performed by Eco Recycling.
Status: 100% complete.
During this activity the following expected results were produced: the list of raw materials, products and wastes (characteristics, consume and production); the quantified flowsheet with the identification of the flow rate and composition of all streams; equipment specifications (materials and dimensions).
The main results obtained in B6 were:

- process flowsheet optimization. It was determined including a detailed description of flow rate and composition of any identified stream. For this purpose, a processing capacity of 200 ton/y was set and data previously derived by lab scale research activities (action B1) were exploited. Reported data identify, in line with expected results of action B6, the consumption of reactants and the productivity of prototype's glass.
- preliminary design of main plant units. In this framework, mechanical treatments were identified as the technological solutions to be adopted for mechanical pretreatment of panels. Preliminary design of solvent extraction unit was presented. The required volume of such unit and the power of the impeller needed for the agitation of suspension were determined.

5.1.7 Action B7 Pilot plant design (including offer request)

This activity has been completed in the period 1st October 2014-30 June 2017; starting date: 1st October 2014. The action started 1 month before the date foreseen at the beginning and was concluded in June 2017 with a considerable delay respect to the foreseen ending at the beginning (June 2015). The delay was related to the mechanical section design caused mainly by the difficulties in finding the most suitable system to shred the panels and in finding suppliers able to deliver the innovative equipment based on the design requested. Eco Recycling asked for feedback on the preliminary design of the mechanical unit to the partner which had to purchase it. However, the delay in receiving

feedback restrained Eco Recycling to complete the design in the foreseen time. Anyway, the action was completed and all the expected results reached (Deliverable B7). This action was implemented by Eco Recycling.
Status: 100% complete.
Eco Recycling has dealt with the design, purchase, and built of the whole prototype unit.
Both the physical (solvent treatment) section and the mechanical pretreatment section have been especially designed and realized for the specific processing of photovoltaic panels.
The prototype was designed specifically for the treatment of photovoltaic panels and represent a highly innovative element, resulted from engineering expertise of qualified personnel. In fact, a plant with these features had never been realized and used for solar panels treatment. The prototype has also been designed and built to conduct a specific innovative patented process ("Process for treating spent photovoltaic panels"; publication N°: W02014184816A1, application N° PCT/IT2014/000124; registered on 09/05/14).
Regarding the mechanical pre-treatment section, it has been especially designed and realized for the specific processing of PV. It is made up of a series of components that together form an original structure that is not available as a standard product nor has ever been commercialized.
Therefore, especially for the project's purposes, a section with processing capacity comparable to those of a prototype scale for demonstrative purposes (about 150 kg/h) was created. In addition, all the equipment was installed in a container and assembled using closed interlocking, feed charge and products discharge devices. This prevented the dispersion of glass powder in the atmosphere. Furthermore, the shredder control grid has been optimized to achieve a suitable granulometric distribution. The sieves size was also defined to obtain 3 separate fractions suitable for the downstream processes (coarse fraction in the solvent treatment unit and intermediate and fine fractions in leaching unit). The section has also been designed to obtain a suitable material for the subsequent solvent and chemical treatments, required in the process. Therefore, the physical treatment section is complementary to the chemical section of the prototype. The two sections together form a totally innovative prototype and can carry out the entire cycle of treatment.
The layout of the plant was developed according to the project description with one main difference represented by the installation of both the physical and mechanical units in two containers adequate to be charge by a crane and move as needed. This solution was considered useful to increase the impact of the pilot plant by offering the opportunity to demonstration, of the proposed process at any collection point. This would remove the need to bring panels to the plant offering an effective solution to possible logistic difficulties. Further, the possibility to bring the plant wherever requested will also in the future allow the organization of demonstration exhibitions to significantly increase the project dissemination even after the project end.
The main objectives achieved in B7 action were:

- Definition of the sequence of operations to be performed (including the description of each operation);
- Definition of the equipment specifications;
- Detailed design specifications were fixed and requests for offers were submitted for all the plant equipment,
- For both the mechanical and the solvent treatment section, offers were requested.
  Electrical energy consumption of the plant was computed-,
- Plant and control system design;
- Elaboration of the detailed P&I diagram including piping design and definition of any actuator and sensor required to implement the formulated operational procedure;
- Definition of control topology and human machine interface needed to carry on the process automatically;
- Elaboration of the plant layout.

5.1.8 Action B8 Pilot plant construction (including site preparation and authorization request)

This activity has been completed in the period 1st December 2014-30 June 2017; starting date: 1st December 2014. This action was extended respect to the first Gannt of 20 months caused mainly by the problems occurred with the inability of Eco Power and Green Engineering to purchase their part of the prototype. The activities performed in this action were detailed in the Deliverable B8 including the draft operational manual of the prototype also describing monitoring and control systems. The action was completed by Eco Recycling, HTR, Eco Power and Green Engineering.
Status: 100% complete.
Although some delay occurred during this action due to *Economic issues* and *Technical issues* (Paragraph 4.2 of this report) they did not preclude to complete the action and reach the goal of building the plant.
As regards the authorization procedure, Regione Lazio (the competent authority) already gave to EC the permission for the treatment of WEEE in a hydrometallurgical experimental plant. This authorization referred to a plant placed in a container at Civita Castellana EC industrial site were a pilot plant able to perform chemical treatments on pre-treated WEEE is located (plant built in the HydroWEEE Project, FP7 EU project). In addition, in order to comply with regional obligations and to operate the plant in a short time, a guarantee policy has been signed. Since the new prototype Photolife also processed electric and electronic components it was considered possible to relate this new activity with the already authorized one. In fact, the Photolife plant was considered (in accordance with Regional Rules) an integration of the existing plants. Accordingly, Regione Lazio accepted a simple application form for the integration of already existing authorized plant.
The containers (the HydroWEEE and the Photolife) located in the same platform in Civita Castellana were integrated for wastewater and utilities.
The results reached in B8 action have been:

- The realization of the prototype for the physical treatment including:
    - Elaboration of detailed P&I diagram including piping design and definition of any actuator and sensor required to implement the formulated operational procedure;
    - Plant layout;
    - Technical equipment specifications;
- The realization of the prototype for the mechanical pre-treatment of the photovoltaic panels including:
    - Elaboration of detailed P&I diagram;
    - Plant layout;
    - Technical equipment specifications.

For the solvent treatment section, the commissioning tests were carried out in the manufacturing companies site while the running tests were carried out in the Eco Recycling industrial site. To determine optimal mixing conditions in the liquid bulk to optimize solid / liquid contact and, consequently, process efficiency, accurate fluid dynamics analysis was conducted by the company Technosind srl.
For the mechanical section the manufacturer tested the single equipment to verify the single device performance. The equipment were then connected and the whole structure was tested.
The solvent treatment and the mechanical pre-treatment units were located inside two different mobile containers and connected to the electrical and hydraulic grid of the site. The physical treatment section has a potentiality of 200 ton/y while the mechanical pre-treatment unit has a potentiality of 150 kg/h.
The interconnection of these new units with the pre-existing pilot plant for the hydrometallurgical treatment (HydroWEEE) was made.
The connection with the hydrometallurgical plant was performed by accumulating the intermediate and fine fraction in a dedicated box. The sample accumulated was treated when the desired amount of material for chemical treatment was reached.
As for connection with the wastewater treatment, although the water used in the process is recirculated, the discharge water from preliminary tests has been collected and stored in cubic tanks

and then sent to the wastewater plant. The wastewater emerging from HydroWEEE plant was partially reused in leaching while the purge fraction was stored and then sent to wastewater treatment plant.

5.1.9 Action B9 Disassembling and physical treatment: optimization using Si- and CdTe-based panels

This activity has been completed in the period 1st October 2015-30 July 2017; starting date: 1st October 2015. This action was extended respect to the first Gannt of 14 months caused mainly by the mentioned delay in mechanical treatment construction. The activities performed in this action were detailed in the Deliverable B9.
The activity was performed by Eco Recycling which carried out experiments in pilot plant and HTR characterized the products obtained in the different operating conditions in order to optimize the treatment. The activity was developed in collaboration with Eco Power.
Status: 100% complete.
The panels used in the Photolife project were collected and catalogued. These panels presented different characteristics as constituent components and the presence of an aluminium frame, which had to be removed before feeding the module in the downstream processes. In the disassembling activity the frame was mechanically manually removed.

The first process step is the crushing of the panels without the frames and subsequent screening to separate the three specific granulometric fractions from the shredded sample.
Different campaigns have been carried out to determine the best technology for the mechanical pre-treatment for both Si-based and CdTe panels. The data collected in these preliminary tests have contributed to the design of the specific shredding unit for the PV. After this section was built, several campaigns have been conducted using the equipment designed and optimized for the Photolife to achieve a specific particle size distribution that best suited the process specifications.
From these campaigns was collected a quantity of Si based panels coarse fraction equal to 638 kg. This fraction was sent to the prototype' solvent treatment unit for the demonstration phase. From the mechanical treatment 255 kg of intermediate and fine fraction were collected and were sent to the chemical treatment section for tests.
Regarding the CdTe panels, a quantity of coarse fraction equal to 470 kg was obtained in the mechanical section which were then sent to the prototype' solvent treatment section. From the mechanical treatment 261 kg of intermediate and fine fraction of CdTe panels were sent to the chemical treatment section for tests.
The coarse fractions obtained from PV shredding were used to carry out experimental campaigns in the solvent treatment section (637 kg of Si-based and 469 kg of CdTe coarse fractions were treated). The two types of panels were treated separately to compare the results obtained from each category. The results obtained from the numerous campaigns were very satisfactory.
Around 510 Kg of clean coarse glass from Si-based panels physical treatment and 413 Kg of clean coarse glass from CdTe panels physical treatment have been recovered.

5.1.10 Action B10 Chemical treatment: optimization using Si- and CdTe-based panels

This activity has been completed in the period 1st June 2016-30 July 2017; starting date: 1st June 2016. This activity started with delay respect to the scheduled starting date foreseen at the beginning and was extended of 4 months respect the initial time scheduling.
The activities performed in this action were detailed in the Deliverable B10. The action was performed by Eco Recycling which carried out experiments in the mobile pilot plant and HTR characterized the products obtained in the different operating conditions in order to optimize the hydrometallurgical treatment.
Status: 100% complete.
This action purpose is to perform a chemical treatment on the intermediate and fine fraction emerging from mechanical pretreatment section. Treatment of the intermediate fraction made possible the

recovery of clean glass. Lab scale results put in evidence that according to the different types of panels different metals were found. In particular Ti, Ag, Zn, Fe and Al are present in Si-based panels (mono-crystalline, polycrystalline and amorphous Si panels), while Cd, Te, Zn, Al and Fe are present in CdTe panels.
Intermediate fractions of both Si and CdTe panels (182 and 204 kg, respectively) were treated with an acid leaching in order to recovery directly clean glass. Then the solid obtained resulted in a totally clean glass. However, the fine fractions of Si and CdTe panels (72.5 and 56.5 respectively) were treated separately through a hydrometallurgical process developed with the intent to obtain metal concentrates selectively. In this way several tests of basic leaching followed by leaching and acidification were carried out resulting in two detailed processes in action B10.
Chemically treated the intermediate fractions, around 175 Kg of clean glass from Si-based panels and 196 Kg of clean glass from CdTe have been recovered.
Chemically treated the fine fraction, around 72.2 kg of solid containing Ag and TiO_2 and 0.43 kg of metal concentrate (Al and Zn) from Si-based panels and 55.8 kg of solid residue and 0.09 kg of metal concentrate (Te, Al and Zn) from CdTe have been recovered.

5.1.11 Action B11 Wastewater treatment: optimization

This activity has been completed in the period 1st June 2016-30 July 2017; starting date: 1st June 2016. This action was extended respect to the first Gannt of 6 months caused mainly by the already mentioned delay in plant construction. The activities performed in this action were detailed in the Deliverable B11. The activity was implemented by Eco Recycling which carried out experiments at the industrial site's wastewater facilities and HTR characterized the streams obtained in the different operating conditions in order to optimize wastewater treatment.
Status: 100% complete.
During the demonstration activity in the different sections of the Photolife Prototype, two different wastewaters were generated and an exhausted solvent stream.
The first wastewater came from the liquid used in the process. The amount of wastewater generated by this operation was lower than the initially estimated quantity. In fact, this liquid has been generally re-used in the process; only sporadic purges were done due to the contamination by a polymeric material's particulate and solvent. Only little discharges were needed as it was seen that although the liquid contained suspended solids and traces of solvent, it did not compromise the yield of the separation.
The purges were accumulated in external tanks where the liquid contained in the storage tank was also conveyed during a plant maintenance operation.
These wastes were treated and disposed by GSA, a company specializing in environmentally friendly services and solutions, with their headquarter near the Eco Recycling's plant.
The second wastewater produced in the demonstration activity, was obtained from the leaching operations. This water has been repeatedly used in the process; finally, the wastes were giving to GSA for secondary refining treatment (distillation and membrane reactors), after a pretreating in the hydrometallurgical section by precipitation.
Concerning the part of the solvent used in the treatment remained trapped in the polymer matrix, it was recovered and reused in the process.

5.1.12 Action B12 Experiments using innovative photovoltaic panels

This activity has been completed in the period 1st June 2016-30 July 2017; starting date: 1st June 2016. The activities performed in this action were detailed in the Deliverable B12. This action was extended respect to the first Gannt of 6 months caused mainly by the already mentioned delay in plant construction and the initially difficulties in retrieve innovative panels. This action was implemented by Eco Recycling and HTR.
Status: 100% complete.

The innovative panels that were collected and then treated in the pilot plant are the CIGS category. These panels haven't an aluminum frame but own connection cables that were removed before feeding them to the mechanical section. The mechanical treatment was realized through a shredder unit that produced fractions with different granulometric distributions. Different campaigns have been carried out to determine the best technology for the mechanical pre-treatment of the CIGS-based photovoltaic panels.
Several campaigns have been conducted using the equipment designed and optimized for the Photolife project to achieve a specific particle size distribution that best suited the process specifications.
From these campaigns was collected a quantity of coarse fraction equal to 659 kg that was sent in the solvent treatment unit for the demonstration phase.
From the mechanical treatment 365 kg of intermediate and fine fraction were collected and were sent to the chemical treatment section for tests.
An amount of 623 kg of coarse fractions were used to carry out experimental campaigns in the solvent treatment section. The glass output from the treatment is resulted to be clean confirming the results obtained in the laboratory experimentation. Future activities foreseen the glass samples produced by Photolife will be sent to the "*Stazione sperimentale del vetro"* (Murano, Italy) to confirm the glass purity.
The activity of B12 action will continue even after the end of the project as it is intended to analyze other glass samples output from the pilot plant tests to verify the quality of the glass.
Around 743 Kg of clean glass obtained by treating the coarse and intermediate fraction respectively in the physical and chemical units have been recovered.
We treated 202 kg of the intermediate fraction by a leaching process was in order to obtain totally clean glass. On the other hand, 163 kg of CIGS fine fraction was subjected to a chemical treatment that consisted of acid leaching with the same optimized characteristics described in action B15. Then the precipitation of the extracted metals occurred, allowing the obtainment of 162.8 kg of a solid residue and 0.24 kg of the metallic concentrate.

5.1.13 Action B13 Product Characterization

This activity has been completed in the period 1st January 2016-30 July 2017; starting date: 1st January 2016. The activities performed in this action were detailed in the Deliverable B13. This action was extended respect to the first Gannt of 6 months caused mainly by the already mentioned delay in plant construction. This action was implemented by HTR.
Status: 100% complete.
In this action, crushed materials emerged from first campaign of crushing were used as input materials for the characterization of the products. At the end of mechanical treatment a coarse, intermediate and a fine fraction are obtained. Coarse fraction was then submitted at lab scale to solvent treatment in different operating conditions in order to evaluate the product yield and characteristics. The fine fraction was chemically characterized to assess composition and chose which fractions have to be treated for glass recovery and which other for metal recovery. These tests confirmed the good separation property of the solvent treatment giving high quality solar grade glass (Fig.6) from the treatment of the Si-panels coarse fraction 80% as weight of initial wastes treated depending on the operating condition of mechanical pretreatment and the solvent treatment conditions.

Fig.6: Solar grade glass

5.1.14 Action B14 Economic analysis and management strategies

This activity has been completed in the period 1st February 2017-31 August 2017; starting date: 1st February 2017. The activities performed in this action were detailed in the Deliverable B14. There was no delay in the completion of the action which was implemented by Eco Recycling.
Status: 100% complete.
Implementation of material and energy balances obtained by the pilot plant tests have been used to simulate the Photolife process using both a specific software and calculate sheets property of Eco Recycling to study the technical and economic feasibility of the project. The flux of material and possible revenues during next years have been evaluated for the use of the realized pilot plant with a potentiality of 200 ton/year. Economic analysis has been performed considering such balances including the costs for solid and wastewater treatment and preliminary estimates for products selling price. Different scenarios have been studied by changing the end application of the intermediate and coarse fraction; the clean glass price and the disposal price for the treatment in the pilot plant. The parameter obtained and compared in the different case was the payback time (PBT); this represents the parameter to define the economic feasibility of a process related to the potentiality of the plant.

5.1.15 Action B15 Lab scale treatment of innovative photovoltaic panels

This activity has been completed in the period 1st January 2015-31 May 2017; starting date: 1st January 2015. The activities performed in this action were detailed in the Deliverable B15. This action was extended respect to the first Gannt of 13 months caused mainly by the initially difficulties in retrieve innovative panels and was implemented by HTR.
Status: 100% complete.
In total, ten CIGS panels were retrieved from Eco Power and Green Engineering and used for these tests, being 6 Mia Solé (due to the big amount collected), 2 Solyndra and 2 Solibro. Solyndra, which is a specific type of CIGS panels present tubular shape with three concentric tubes filled with silicon oils. According to this peculiar shape and composition this kind of PV required a preliminary manual dismantling for silicon oil emptying. Then two external tubes can be directly recovered, while the internal tube required a chemical treatment for the extraction of the active metals deposited on its external surface. Solyndra and Solibro are both flat type panels, which were crushed by the mechanical treatment and directly submitted to physical and chemical treatment. By this way copper,

indium, gallium and selenium can be extracted in liquid phase for possible exploitation while glass is cleaned for recycling.
Solyndra panels internal tubes covered by active CIGS materials and Solibro flat panels were used for tests concerning leaching optimization and product recovery. Parameters like leaching agent type, concentration of leaching agent, temperature and duration of the process were investigated. More specifically quantitative extraction of target metals was achieved using concentrated nitric acid. Alternatively, sulfuric acid and hydrogen peroxide allowed 99% extraction yields in specific conditions detailed in B15 action.
Two different treatment routes were designed for Solyndra and Solibro panels. Basically, milled Solyndra cylinders were leached with acid and submitted to precipitation in order to form a metallic concentrate. On the other hand, coarse fraction of Solibro panels were treated with solvent resulting directly clean glass. Fine fraction was submitted to acid leaching and further precipitation allowing the generation of a metallic concentrate which was characterized with Solyndra concentrates. In the end of this action, about 2 kg of fine fraction were treated giving 25 g of metallic concentrate.

5.1.16 Action C1 Environmental assessment of the project impacts

This activity has been completed in the period 1st October 2014-31 August 2017; starting date: 1st October 2014. The activities performed in this action were detailed in the Deliverable C1. This action did not have any delay and was implemented by Eco Recycling with the collaboration of Green Engineering and Eco Power.
Status: 100% complete.

C1.1 Monitoring the environmental impact of the pilot plant activities during the project

This subaction of C1 activity is related to the monitoring of the environmental impacts during demonstration activities in the Photolife prototype (August 2015 - July 2017). The action was extended to July 2017 due to the delay in building the mechanical section to perform some monitoring measurements (acoustic pollution and powder emission).
Status: 100% complete.
This subaction of C1 activity is related to the monitoring of the environmental impacts during demonstration activities in the Photolife prototype (Actions B9-B12).
The project Photolife has the aim to realize a prototype for photovoltaic panel recycling, which, although on a pilot scale, allowed running the entire work cycle on end-of-life modules. It was considered essential, therefore, in view of the implementation of a full-scale plant, to assess the possible environmental impacts of the process designed and to define the measures to be taken to contain wastewater process and the emission.
For this reason, they were then evaluated: the quantities of metals present in the wastewater, the noise pollution generated by the operating phase on the plant and the emissions of organic vapors (during solvent treatment of coarse fraction) and powders release during mechanical pretreatment into the atmosphere.
At the beginning a preliminary analysis of the suitable equipment for assessing pollution release during project implementation was done. Later it was chosen to appeal to specialized personnel rather than to carry out measurements of the emission variables identified through commercial instruments. The choice to make discrete measurements with sophisticated instruments rather than continuous measurement with commercial tools was made for two reasons: 1) it was not considered necessary to monitor the plant over a long period of time as its operation was constant and has not unexpected changes during the operation and consequently in emissions expected 2) it was considered more relevant to get more reliable data released by technicians specializing in this sector rather than the ones obtained using commercial tools.
For each pollutant specific monitors were carried out by specialized operators.
Other pollutants present in the wastewaters emerging from the hydrometallurgical section was heavy metals, whose quantification has been performed collecting sample and analyzing them in HTR laboratories by Atomic Absorption Spectrophotometer.

C1.2. LCA

This subaction of C1 is related to the Life Cycle Assessment of the Photolife project (October 2014 – November 2014; May 2015 – December 2015; October 2016 – July 2017; starting date: 1st October 2014). This action was extended respect to the first Gannt of 3 months caused mainly by the already mentioned delay in plant construction.

Status: 100% complete.

The LCA carried out within the Photolife project had the general objective to identify the main environmental aspects and stages of the entire recycling cycle of photovoltaic panels at the end of life, based on the processes developed and demonstrated within the LIFE project.

The life cycle impact assessment categories evaluated in this study are from the ILCD recommendations in the European context. Only those that resulted to be significant from a first run of the LCA were considered: climate change, acidification, resource depletion, photochemical ozone formation and human toxicity and freshwater eco toxicity.

Target audience was both internal in the project and external. In the first case, the achieved results were used to optimize the recycling process in terms of the environmental impact, and the LCA was performed iteratively during the whole project. In the second case, the external stakeholders of the Photolife project were decision makers and public authorities.

At the action beginning main activities performed have been the following: statement of the goal and scope of the LCA; Life Cycle Inventory analysis; preliminary LCA based on literature data and lab scale results comparing the Photolife process with the disposal of the panels in landfill.

The LCA permitted to quantify the environmental impact of the recycling processes developed and demonstrated within the LIFE project, and to compare this management strategy with the disposal in landfilling site. The functional unit was 200 tons of PV panel that is the capacity of the prototype.

A further study has been produced after the construction of the pilot plant. The LCA study was performed on a sample of 1000 kg of photovoltaic panels at the end of life by comparing environmental impact resulting from two scenarios: the use of the thermal process and the use of the Photolife process. In this analysis the optimized energy and material balances obtain during the project have been used.

The most critical steps resulted to be the shredding operation (due to the high energy request) and the solvent treatment.

The analysis showed that the solvent process is preferable from the environmental impact point of view: the main reason is the ability of the process to recover a high added value glass respect to the one obtained with the thermal process.

In general, different behaviors have not been observed for the different panels analyzed, except for the major credits generated by the recovered aluminum that is contained in the polycrystalline silicon based panels frames.

C 1.3 Preliminary environmental impact assessment and financial prevision for future full-scale plant

This subaction of C1 is related to the preliminary assess for a scale up of the Photolife pilot plant (1st December 2016 – August 2017; starting date: 1st December 2016). There was no delay in the completion of the action.

Status: 100% complete.

To prepare a preliminary business plan for the full-scale plant, the material balances obtained by the HTR lab scale activity have been collected.

As a result, a basic economic feasibility analysis was conducted for three production cycles with different processing capacities trying to determine which productive capacity gave a reasonable and acceptable payback time.

The data used during this first pre-feasibility analysis were updated with those obtained from prototype experimentation. Using these new data for the material and energy balances, it was possible to develop a new business plan and assess the environmental impact of the industrial plant.

Furthermore, a destination market was found for all products output from the Photolife process. In order to fix the plant cost the "0.6 power rule" was used.

5.1.17 Action C2 Assessment of socio-economic impacts

This action began on 1st December 2016 and ended on 31 August 2017. There was no delay in the completion of the action which was performed by Eco Recycling. The activities performed in this action were detailed in the Deliverable C2.

Status: 100% complete.

Based on the results obtained by processing the shredded PV in the innovative Photolife pilot plant, it was observed that the recovered and recycled rates met the requirements of the European Directive specific for those RAEE (Directive 2012/19 / EU). For this reason, it has been considered useful to use the prototype to handle other types of WEEE (R3, R4, and R5 category). The innovation of the end-of-life process coupled with the versatility of the equipment used in the prototype has favoured the emergence of a series of new working opportunities for the population resident in the areas adjacent to the site where the prototype is placed. This aspect has raised considerable interest among the local citizen. The innovative process efficacy, as well as the resonance that has come from industry experts, has attracted the attention of a number of stakeholders whom have expressed interest in building what will be the first industrial plant for the end of life PV recycling.

5.2 Dissemination actions

D1 General dissemination

This activity has been carried out throughout the duration of the project (1st June 2014-31 August 2017). A description of the updated dissemination plan is fully reported Deliverable D. The action was implemented mainly by Eco Recycling supported by the partners HTR, Green Engineering and Eco Power.

Status: 100% complete.

More specifically achieved results were:

1) A link to the project website in the **Facebook** page of Eco Recycling has been created to increase the advertising of Photolife Project through the social network (https://www.facebook.com/Eco-Recycling-Srl-928331023861948/?fref=photo);
2) The target groups **mailing list** was initially prepared by the network of project partners and was expanded through the acquisition of additional stakeholders from internet. Through the pursuit of the Action B7 was possible to add new contacts;
3) To promote the dissemination of the project, 500 **brochures** were printed and distributed during the various stages of the project at various events including the open day and the final conference. Two types of brochures were realized: the first one at the beginning and contains general information about the project; the other one has been updated with the most significant project results and was released after the prototype was built;
4) The first **press** has been released by the magazine "HIGH Tech Ambiente" (http:/photolifeproject.eu/updates/679/photolife-project-hi-tech-ambiente-press-release) on 01/02/16. Main contents were: general description of Photolife Project, PV recovery process and pilot plant explanation. The magazine choice for the first press of the project is a monthly paper with a national circulation of over 20,000 copies certified. The magazine has long been the leader in environmental information and it provides a complete overview of the technological innovation in the environmental sector. This magazine is also choice for the dissemination activity of some LIFE projects. It is the official organ of Assita - Italian Association of Environmental Technologies and it's associated with EEP (European Environmental Press).

The second and the third press of the Photolife project were released on the "Campo de' Fiori" magazine, the first on July 2017 and the second one on August 2017. Respectively their main contents are: a general overview of the Photolife including the mechanical pretreatment section and the interview to Prof. Luigi Toro after the open day (the event was attended even by the press). "Campo de' Fiori" is a monthly paper with the newspaper office in Civita Castellana, where the Photolife Prototype is located. Another press release was made by the University of L'Aquila to promote the Photolife project at the beginning of the project. Another press release about the project results and the Photolife process illustration was presented at HA PARTS & COMPONENTES and is currently in press.

5) A **web site** (www.photolifeproject.eu) dedicated to the project was on line since 31 August 2014. It contains the description of the project objectives, actions and expected results. Important achievements within the project have been published, as well as news, press release, reports of all dissemination events and pictures of the pilot plant. Furthermore, brochures and other information paper, as newsletters, are available for download. The web site has been regularly updated and will be preserved for at least five years after the end of the project.

6) Presentation of the project at 5 **congresses** were done:

- **Sustainable Industrial Processing Summit & Exhibition, SIPS 2014,** 29 June-3 July 2014, Mexico. Presentation: "*Photovoltaic panel recycling: from type-selective processes to flexible apparatus for simultaneous treatment of different types"*. Francesca Pagnanelli, Emanuela Moscardini, Thomas Abo Atia, Luigi Toro. Individuals attended the conference about 50. Website photo gallery: http://photolifeproject.eu/galleries/678/shechtman-international-symposium-cancun-2014 Website update: http://photolifeproject.eu/updates/661/shechtman-international-symposium.
- **Ecomondo** 05-08/11/2014, Rimini, Italy: fair on the most sustainable and advanced technological solutions for the proper management and recovery of all type of waste; efficiency in the use and processing of raw materials and the use of renewable raw materials. Individuals attended at the fair about 500. Website update: http://photolifeproject.eu/updates/660/ecomondo-2014.
- **Sustainable Industrial Processing Summit & Exhibition, SIPS 2015**, 4 - 9 October 2015 Antalya, Turkey. Presentation**:** "*Process and automated pilot plant for simultaneous and integral recycling of different kinds of photovoltaic panels"*. Francesca Pagnanelli, Pietro Altimari, Emanuela Moscardini, Thomas Abo Atia, Luigi Toro. Individuals attended at the conference about 50. Website update: http://photolifeproject.eu/updates/671/sustainable-industrial-processing-summit-exhibition.
- **Life-MED Project Conference**, Brescia University, Brescia, Italy. Brescia University as part of the LIFE MED Project, organized two training days entitled: '*Classification and waste management in health facilities*'. LIFE MED Project proposed a new integrated system to reduce waste from medical equipment and WEEE. The event was aimed at professionals in the field of waste management. During the initiative, there was a section dedicated to the Presentation of the Italian LIFE projects on the Waste Electrical and Electronic Equipment (WEEE). The event was an important opportunity for collaboration, dissemination and networking. Individuals attended at the conference about 30. Website photo gallery: http://photolifeproject.eu/galleries/676/life-med-weeenmodels-and-photolife-brescia-20-210126 Website update: http://photolifeproject.eu/updates/675/cauto-cooperative-training-days-classification-and-waste-management-health-facilities.

- **WEEEnModels Project** Worhshop, Festival della Scienza, Genova 3 November 2016. The meeting represented an opportunity for the LIFE projects and experts to discuss about different aspects related to the WEEE recovery and the elements necessary to make sure that the new WEEE collection and recovery targets can be achieved. Since the workshop was held during the "Science Festival" in Genova, and the Photolife project presentation was disclosed in the book of the event, it was an important opportunity to declare the Photolife Project. Individuals attended at the conference about 40. Web site photo gallery: http://www.photolifeproject.eu/galleries/687/weeenmodels-life-project-workshop
  Website update: http://www.photolifeproject.eu/updates/686/where-are-weee-going-workshop

7) Four **presentation to interest groups or stakeholders**.

8) Publications in **journals of the field:**

   a) Paper in scientific journal:

      a.1) F. Pagnanelli, E. Moscardini, P. Altimari, T. Abo Atia, F. Beolchini, L. Toro Thermal versus solvent treatment for material recovery from end of life photovoltaic panels: environmental and economic assessment (submitted to Waste Management)

      a.2) F. Pagnanelli, E. Moscardini, G. Granata, T. Abo Atia, T. Havlik, L. Toro, 2017 (online 2016) Physical and chemical treatment of end of life panels: an integrated automatic approach viable for different photovoltaic technologies, Waste Management, 59, 422-431.

      a.3) Francesca Pagnanelli, Emanuela Moscardini, Thomas Abo Atia, Luigi Toro. (2016) Photovoltaic panel recycling: from type selective processes to flexible apparatus for simultaneous treatment of different types Mineral Processing and Extractive Metallurgy Transactions of the Institutions of Mining and Metallurgy: Section C, 125 (issue 4) 221-227. DOI: 10.1080/03719553.2016.1200764

   b) Proceedings:

      b.1) Francesca Pagnanelli, Emanuela Moscardini, Thomas Abo Atia, Luigi Toro Photovoltaic panel recycling: from type-selective processes to flexible apparatus for simultaneous treatment of different types. Proceedings of the SHECHTMAN INTERNATIONAL SYMPOSIUM, 29 June - 04 July 2014 Cancun, Mexico. Sustainable Industrial Processing Summit Volume 4 (Recycling, Secondary Battery) pag. 279-294. ISBN CD Set: 978-1-987820-11-9, ISSN: 2291-1200 Editor: Florian Kongoli. Produced in Canada (oral presentation held);

      b.2) Francesca Pagnanelli, Pietro Altimari, Emanuela Moscardini, Thomas Abo Atia, Luigi Toro First outcomes from PHOTOLIFE PROJECT: Process and automated pilot plant for simultaneous and integral recycling of different kinds of photovoltaic panels Proceedings of the Sustainable Industrial Processing Summit & Exhibition (SIPS 2015) 4 - 9 October 2015, Antalya, Turkey. Volume 11: RECYCLING & ENVIRONMENTAL pages:67-80 (sips 15 7 48 FS) Edited by F. Kongoli, T. Havlik, F. Pagnanelli Publisher: FLOGEN STARS OUTREACH Publishing date: December 2015 ISBN 978-1-987820-34-8 (CD) Metals and Materials Processing in a Clean Environment Series: ISSN 2291 1227 (CD) (oral presentation held);

      b.3) Francesca Pagnanelli, Emanuela Moscardini, Thomas Abo Atia, Pietro Altimari, Luigi Toro. Physical and chemical treatment of end of life Si-based and CdTe photovoltaic panels. Proceedings of the SHECHTMAN INTERNATIONAL SYMPOSIUM, 06-10 November 2016 Sustainable Industrial Processing Summit

Volume 10 (Battery, Recycling, Environmental, Mining) pag. 57-66. ISBN 978-1-987820-54-6, ISSN: 2291-1227 Editor: Florian Kongoli. Produced in Canada.

9) Two **visits on demand** were carried out at the Photolife plant site allowing to show to national and international stakeholders the two sections of the prototype and how they work.

10) Eco Recycling organized an **open day** at its operational headquarters at Civita Castellana (VT), where national and European stakeholders, specialists and citizens were invited to visit the plant. Many people have joined at this event, having the chance to visit the two sections of the Photolife prototype. A guided tour of the plant by Eco Recycling staff was made. In this occasion, the samples from the mechanical treatment section and the clean glass from the physical treatment section were shown.

11) On July 24th, at the Eco Recycling's operative office in Via di Vannina 88, Rome (Italy), the **Final Conference** of the PhotoLife Project was organized. The event was attended by the hosting company Eco Recycling, the Photolife partners (High Tech Recycling Center, Eco Power and Green Engineering) and some companies and research groups who welcomed the invitation to present their latest and innovative international projects.

D2 Mandatory dissemination
This activity has been carried out throughout the duration of the project (1st June 2014-31 August 2017). Details about achieved results are reported in Deliverable D. The activity was implemented by Eco Recycling.
Status: 100% complete.
More specifically the results obtained for this action were:

1. A web site (www.photolifeproject.eu) dedicated to the project was on line since 31 August 2014. The website has been regularly updated and will be preserved for at least five years after the end of the project. Eco Recycling was responsible for the overall implementation of the website, while partners are committed themselves in providing contents and update. The visitors from the beginning to the end of the project were 4967. This remarkable result is attributed to an intense activity of uploading website contents as the photo galleries, the newsletters, the news, and networking which stimulated the interest of the people.
2. A LIFE-project notice board was set in the industrial site of Eco Recycling near the entrance of its platform where technical activities were carried out. Furthermore, Eco Recycling, HTR, Green Engineering and Eco Power applied a plate at their buildings. The LIFE logo was always present on the plates.
3. 500 copies of Layman's report (half copies in Italian and half in English) were printed and distributed to people of interest and during the Open Day and the Final Conference. Within the Layman's Report there is a detailed description of the project's objective and of the prototype built, the document has been written in a no technical language to permit to no specialist audience to easily understand the project.

NETWORKING (Deliverable D)
During the project, intense **networking** activities with other LIFE projects have been made, with discussions on the state of progress of their projects and possible future collaborations on topics related to the disposal of wastes through innovative processes. The projects with which the networking activities were carried out have been mainly:

- The LIFE-MED project which deals with the management of discarded medical equipment and devices. The project addresses primarily the environmental problem of sustainable waste and natural management; it supports waste prevention programs and measures to promote the application of the waste hierarchy. A presentation of Photolife project was done at the LIFE-MED conference on 21/01/2016;

- The FRELP project which aims to test and develop innovative technologies for recycling of end-of-life PV panels in an economically viable way using also a thermal process. Eco Recycling joint the invitation at the conference on 25/09/2015;
- The WEEEnModels project which aims to define and implement a new model of WEEE reverse logistics, which was aimed at increasing the collection of WEEE amount by improving the small WEEE collection and increasing the control. Eco Recycling presented the Photolife project at their last conference on 03/11/2016 which concerned the WEEE management and disposal. In order to formalize the collaboration between Photolife and WEEEnModels projects, a document has been signed by the coordinator beneficiaries of both the projects. The parties agree to cooperate on the WEEE theme, promoting the exchange of information regard legislation, state of the art and the reciprocal involvement in future projects on the WEEE area.
- The Reclaim project which aims to recovery Indium and Gallium from flat panel displays (LCD and LED) and CIGS photovoltaic modules. The main goals of Reclaim project is obtain a recovery efficiency greater than 95% and purity of Indium and Gallium in the end of the process greater than 99,99% (commercial grade). Eco Recycling was invited to join the event in Belgium on 02/06/2016.
- The Recumetal which aimed to the recovery of critical metals such as indium (In) and yttrium (Y) from discarded flat displays panel (FPDs). For this purpose, during the project, a pilot plant is being designed and constructed. The first contacts with Recumetal was taken on March 2017.

POLICY IMPLICATION (Deliverable D)
On 20 April 2017, a meeting was held between representatives of both the Italian Ministry of Environment and HTR and Eco Recycling. The goal of this meeting was to feature the Photolife project focusing attention on the innovative technology developed. The meeting was also held to establish a sustainable procedure for the disposal and treatment of panels to be included in Italian regulations in accordance with European directives.

5.3 Evaluation of Project Implementation

The methodology of management based on frequent contacts of the coordinating beneficiary with Partners has highlighted promptly the problems (technical and economic) and the difficulties that have occurred gradually over the course of the project. This methodology has allowed Eco Recycling to act quickly so as not to affect results and project time scheduling. The management has been successful. In fact, both the actions and the project's total cost agreed with the ones on the approved project. Some reviews of GANNT and a redistribution of actions (and related costs) among the partners were necessary.
The main results of the project are summarized in the achievement of project milestones.

At the end of the project, all the goals set have been achieved and the results provided a favourable opinion among stakeholders. The main results immediately visible obtained are:

- Good quality of the glass and products obtained in the laboratory phase first and in pilot plant tests later.

- Physical solvent treatment section design, construction, installation and running tests at the EC site of Civita Castellana (Viterbo, Italy);
- Preliminary shredding tests at specialized manufacturers;
- Mechanical pre-treatment section design, construction, installation and running tests at the EC site of Civita Castellana (Viterbo, Italy).

The Dissemination action has been particularly effective. In fact, three presentations have been done to interest groups and stakeholders.

5.4 Analysis of long-term benefits

1. Environmental benefits

a. Direct / quantitative environmental benefits

The current approach for the end-of-life photovoltaic panels' disposal does not include an effective material recovery. Typically, only the panel aluminum frame, when present, and electronic and electric components are separated and appropriately recycled, while the rest of the panel, which is composed of glass, EVA, tedlar and metals, is frequently recovered as contaminated glass and can be hardly reused. A no-dedicated collection and no-specific treatment for end-of-life panels, create a series of environmental problems: no separation of potentially hazardous metals from waste, unmanageable and dedicated panels storage that can create pollution problems as thin glass powders in the atmosphere, illicit disposal of panels that are often illegally assigned to landfills.

The implementation in a large-scale plant of the process proposed in the PHOTOLIFE project will allow for the separation and recovery of the different fractions composing the panels. This will ensure the possibility to reuse high value recovered materials rather than accumulating them in landfills. The dispersion of toxic elements (heavy metals) will be prevent generating, at the same time, a valuable source of secondary raw materials, which ensures a substantial environmental benefit over the disposal practices that are currently used. Currently in Italy a specific PVP treatment aims at recovery high added value secondary raw is not yet present: in fact, the panels are treated with the other WEEE of the same category (R4). Although the joint mechanical treatment of photovoltaic panels with other WEEE in the same category is currently not a problem, since, in their entirety, they still meet the targets set by the European Union, it is necessary to find a solution for the foreseeable future when they will increase exponentially the PVP amounts reached at end-of-life relative to the other R4s weighing significantly on recovery and recycling rates.

The advantages of the proposed process compared to the current disposal practices will be dramatically enhanced during the following years owing to the increasing flux of end-of-life panels. In Italy, the amount of photovoltaic panels installed in 2010 was around 250,000 tons and reached a peak of 1,250,000 t in 2011: since the average panel lifetime is 25 years, a dramatic increase of the flux end-of-life panels can be expected in 2035. Practices including the accumulation in landfills or the recovery of material fractions that can be hardly reused cannot represent a sustainable route to the disposal of this waste flux. Implementation of the proposed process at full industrial scale can in contrast allow recycling the different fractions composing the panel to the production chain, which would in turn support the establishment of a circular economy mechanism.

The project included the construction of a plant with processing capacity of 200 tons of panels per year. During the Photolife project, almost 3 tonnes of different kinds of end of life panels were treated. The analysis of the energy balance evidences that the proposed process can significantly reduce the energy consumption compared to alternative technologies including the thermal treatment of the panel and the landfilling. A preliminary life cycle analysis indicates that the recovery of glass from panels by the proposed process can reduce the greenhouse gas emissions (CO2) compared to the production of glass from primary raw materials.

b. Relevance for environmentally significant issues or policy areas

The project contributes to the objectives of the Environment and Resource Efficiency priority area and, particularly, targets the thematic priorities for Waste and Resource efficiency. Direct contribution to these priorities is attained by the demonstration of a process to separate and recover the different fractions composing end-of life photovoltaic panels. The process fulfills the requirements of the Directive 2012/19/EU by allowing for the recovery of a panel fraction larger than 80%, which can drastically reduce the recourse to landfilling. The process allows recovering fractions that can be reused in the industrial production chain and can thus sustain the development of a circular and green economy.

Project activities can contribute to the objectives of the Climate Action subprogram and, particularly, to the implementation directives described by the "Roadmap for moving to a competitive low carbon economy in 2050" by offering a sustainable lifecycle solution to the application of photovoltaic panels. Particularly, the implementation of the proposed process can minimize the environmental impact of the panel lifecycle and thus support the extended application of photovoltaic in place of technologies for the production of energy that rely on the application of fossil fuels.

The strongest resonance of the project has been in the environmental field: on 20 April 2017, a meeting was held between representatives of the Italian Ministry of the Environment and HTR and Eco Recycling. The goal of this meeting was to feature the Photolife project focusing attention on the innovative technology developed. Other types of disposal have also been analyzed for the photovoltaic panels adopted so far; the current trend in Italy is to treat end-of-life photovoltaic panels together with other WEEE of the same category (R4). However, these current practices are possible just because of the small amounts of end-of-life panels existing now; this trend cannot be an acceptable solution considering the huge increase in PVP waste expected in the coming years. The absence of a specific treatment dedicated exclusively to PVP for the recovery of a decontaminated glass with high added value, has motivated the research group to submit to the authority the current state of the art.

2. Long-term benefits and sustainability

The proposed process allows for the treatment of almost any type of photovoltaic panel currently installed. In this respect, the application of the process can offer a solution to the treatment of photovoltaic panels over the following three decades at least. A plant with processing capacity of 200 tons of panels per year was constructed in action B8 and was operated to process about 3 tons of different kind of panels. Data derived by prototype operation were used to evaluate economic and technical feasibility of the process at larger scale. Processing capacities of about 5000 ton/y, which are consistent with the fluxes of end-of-life panels generated during the following decades in Italy, was considered.

Major long-term benefits derived by the implementation of the proposed process at full industrial scale can be described as follows:

- Environmental: avoid disposal in landfill and thus limit emissions of CO_2;
- Economic - Minimizing the recourse to primary raw materials by the recovery and reuse of any fraction composing the panel;
- Social - companies that will convert old technology into this new technology for WEEE recovery will have a great technological value and will be forced to hire highly qualified staff. The economic benefit will be mainly for stakeholders who intend to build a full scale industrial plant.

3. Replicability, demonstration, transferability, cooperation: Potential for technical and commercial <u>application</u> (transferability reproducibility, economic feasibility, limiting factors) including cost-effectiveness compared to other solutions, benefits for stakeholders, drivers and obstacles for transfer, if relevant: market conditions, pressure from the public, potential degree of geographical dispersion wordwide, specific target

group information, high project visibility (eye-catchers), possibility in same and other sectors on local and EU level, etc.

Photovoltaic panels have been extensively used across and outside Europe over the past two decades. Market analysis performed in action B2 evidenced that several EU countries will face, like in Italy, the need to treat considerably large fluxes of end of life panels during the following decades. This, along with the capability to treat any type of panel, ensures an elevated replicability potential of the proposed technology.

The process developed in Photolife meets the limits imposed by European legislation (Directive 2012/19 / EU), which provides for specific target for the photovoltaic waste management: 80% recovered and 70% prepared for reuse and recycled. It follows that on a European scale it would be convenient to foresee full-scale plants located in the states where the largest quantities of waste from photovoltaic modules are produced (Germany, France and the United Kingdom). This would also be beneficial because existing industrial processes in these states can only handle one type of panel, while the process optimized in the Photolife project is able to handle all the types of photovoltaic modules currently marketed.

This ensures an elevated replicability potential of the proposed technology.

A preliminary economic analysis performed in action B3 evidenced that the economic feasibility can be reached with processing capacities that are consistent with the fluxes of wastes that will be generated in EU countries during the following decades.

Stakeholders were identified expressing interest into carrying on the proposed process at full industrial scale in case of successful demonstration of the constructed prototype plant. The developed technology system can easily be reproduced in other areas as well, furthermore the reagents used are easily obtainable. The most limiting factor could be the absence of photovoltaic waste near the installation site, which would require additional transport costs and difficulties in wastes transport procedures.

4. Best Practice lessons: briefly describe the best practice measures used and if any changes in the followed strategy could lead to possible adjustment of the best practices

Proper recycling of the values in the panel represents a best practice measure. The experimental results on the prototype have provided further indications on how to optimize the process to maximize the recovery of secondary raw materials.

The results of the experimental campaigns carried out on Photolife prototype showed important information for optimizing the process on an industrial scale application. In the industrial plant, will be necessary design an automated system for the mechanical separation of metallic contacts from the shredding fraction. Those metal components will can be re-entered in the precious metals market. The industrial scale plant has been designed to have a very low environmental impact or "zero-waste". In order to achieve this goal, it will be necessary to limit the production of process wastes. Therefore, a solvent distillation unit will be required to allow its almost total recovery and recycling in the process; this would also reduce the solvent make up and consequently reduce this cost item from the budget. As for process water, it will necessary be conveyed to a specific wastewater treatment unit to reuse it completely and thus achieve a closed working cycle.

5. Innovation and demonstration value: Describe the level of innovation, demonstration value added by EU funding at national and international level (including technology, processes, methods & tools, organisational & co-operational aspects)

The proposed process is worldwide innovative, meaning that it is considerably different from any process for the recycle/treatment of end-of-life panels previously proposed and for which research studies or patents have been reported. Alternative recycling processes exhibit several limits: 1) regarding the thermal processes the mainly limits consist of the need to reach high temperatures to detach the EVA and TEDLAR from glass and the impossibility of reusing plastics due to their combustion; 2) selective process as First Solar process for the CdTe are able only to treat one type of panel and are generally high cost process due to the large amount of reagents used. Furthermore, pyrometallurgical processes have a major impact on the "Carbon Footprint" respect to the hydrometallurgical one and permit to obtain only a low-quality glass. None of the existing processes can ensure an adequate cleaning of the recovered glass; the Photolife innovative process involves the production of an excellent quality clean glass that can easily be recycled to the production cycle as high added value secondary raw material. The plant is also able to treat all kinds of photovoltaic panels today on the market.

6. Long term indicators of the project success: describe the quantifiable indicators (percentage of the end of life panels) to be used in future assessments of the project success

Currently and until 2025 throughout the national territory is estimated a quantity of end of life panels (for premature rupture) of 5000-10000 t/year. It is therefore reasonable to build an industrial plant for treat 5000 tones/year of panels (40% of total end of life panel scattered throughout the national country). This data has been confirmed in the economic feasibility study of the plant where a return on investment under 5 years was found.

In 2035 instead, the potential of plant will have to be considerably increased to allow to treat a substantial quantity of panels (62.500 t, 25% according to forecasts of installed panels in 2010 in Italy).