The University of New South Wales
Research and Development Project

UNSW – R&D Project- End-of-Life, highly efficient, low-cost and eco-friendly recycling technology for silicon photovoltaic panels

Project number: 2020/RND015

Appendix D: Interim public dissemination report

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Executive summary

Inspired by metallurgy engineering, the project will develop a highly efficient low-cost closed-loop recycling system to recover valuable metals and silicon from end-of-life (EoL) photovoltaic (PV) panels. The project will leverage interdisciplinary research expertise in metallurgy (pyro-/ hydro-metallurgy), PV, off-gas/wastewater treatment, and collaboration with energy, metallurgy, PV, Silicon (Si), chemical, and recycling industries in Australia and overseas. The system integrates a high-temperature pyrolyser for removing the binding material from panels at high efficiency and productivity, low-temperature leaching reactors using less toxic chemicals to recover valuable metals at high efficiency, and customised waste treatment units to treat/reuse harmful waste gas and wastewater. It will be technically achieved by combining numerical simulations for system design, lab-scale experiments (Milestone 2) and pilot-scale experiments (Milestone 3) for system demonstration, and life cycle/economic/policy analyses for system evaluation. The expected outcomes including lab-/pilot-scale prototypes of PV panel recycling system, up-scalable computer models, and lifecycle/economic/policy analyses, will provide a cost-effective, closed-loop and practical solution to recycling PV panels (targeting >95% silver (Ag), copper (Cu), silicon (Si) recovery; energy consumption <25kWh/kWp), and ultimately allow for a more competitive and sustainable PV industry in Australia and globally.

Project overview

The global total installed capacity for PV has crossed the 900GW mark in 2021 (IEA, Solar PV) and will reach the range of 4.5TW-63.4TW by 2050 (ITRPV). Until 2022, the reported Australian PV installation capacity was over 26GW (Australian PV Institute). With a lifetime of 25-30 years, the EoL PV module waste is expected to reach 630GW (~78 million tonnes) by 2050, with a projected recycling value US$15 billion in 2050 (IRENA and IEA-PVPS). Most EoL PV panels consist of tempered glass as the top surface, Ethyl Vinyl Acetate (EVA) as the encapsulant (by heated lamination) for silicon wafers with metal electrodes, TPT back sheet, and Al frame around the outer edge. NB: the valuable metals contained in the EoL PV panels are quite high, e.g., Ag is ~0.05 wt% high and Cu is ~ 0.11 wt% high. ITRPV2019 reports PV panel recycling will become more important as an environmental challenge and a business opportunity. Specifically, the EoL PV panel may lead to many environmental problems, as solar panels often contain lead (Pb), cadmium (Cd) and other toxic elements, and they may leach into the soil upon disposal in landfills. On the other hand, the EoL PV panels also contain valuable materials like Ag, Cu and Si which can be recycled and reused. However, the current PV recycling technologies are impractically costly attributed to un-optimised reactor/process design, low energy efficiency, and high use of eco-unfriendly chemicals in the delamination and recovery processes. The project aims to develop highly efficient, low-cost and eco-friendly recycling technology for EoL silicon PV panels.

Project update

The milestones in project phase 1 have been achieved. The related modelling studies and experimental studies have been conducted. The lab-scale pyrolysis and chemical leaching prototypes have been established. A couple of advanced numerical models have been developed to deeply understand the physical and chemical phenomena during the end-of-life PV module recycling process, ranging from thermal treatment, physical sieving, and chemical leaching. These models have been employed to support the prototype design and reactor operating condition optimisation. Until now, based on the research outcome in phase 1, five papers have been published in high impact journals and over seven papers are in preparation. One Australian Patent (AU2002903639) has been filed, which proposes a method and apparatus for separating photovoltaic module materials. The developed models and prototypes (lab-scale and pilot-scale) would contribute to the fundamental understanding of PV recycling-related processes and technology iteration, thereby prompting PV industry development in Australia.

Key highlights

- For the first time, multiscale numerical models have been developed to enhance the comprehension of the underlying physics and chemistry involved in the thermal delamination process. These models serve to optimise pyrolysis operating parameters, refine reactor designs, and suggest the most effective technical approaches for achieving exceptional waste PV panel delamination performance.
- A lab-scale pyrolyser prototype is established with the assistance of numerical models, which is applied to systematically study the waste PV panel pyrolysis behaviours and provide key data for numerical model modification and validation. The reactor design optimisation and prototype scale-up could be implemented based on the research outcome.
- The particle-scale chemical leaching numerical model was successfully developed to illustrate the mechanism behind the metal extraction process. This model is employed to support the leaching reactor development.
- A lab-scale chemical leaching reactor prototype was established to conduct the leaching experiments. The accurate reaction kinetics data and metal recovery yields were obtained, which are key information for the numerical model modification and LAC analysis.
- Until now, five papers have been published in high-impact journals and one Australian Patent (AU2002903639) has been filed, which promotes the development of the Australian PV industry.

Lessons learnt

Report 1: Recycling process design, optimisation and scale-up from lab- to pilot-scale

Project Name: End-of-Life, highly efficient, low-cost and eco-friendly recycling technology for silicon photovoltaic panels

Knowledge Category:	**Technical**
Knowledge Type:	Technology
Technology Type:	Solar PV
State/Territory:	NSW

Key learning

PV recycling is a newly emerging area and suitable reactor designs and operational strategy design are not yet available. Thus, the possible reactor designs in terms of e.g., geometry and type, and operation designs in terms of throughput, input rate and temperatures are massive. Constructing such large-scale prototypes to evaluate these designs is unfeasible. Our research focuses on recycling process understanding, optimisation and scale-up from lab scale to pilot scale and then towards industry scale, by means of combining massive but low-cost numerical simulations (based on unique and state-of-the-art numerical techniques available at Shen Lab, UNSW (www.promo.unsw.edu.au) for process design and scale-up, and experimental studies of the selected designs for process demonstration.

Implications for future projects

In future technology development projects, this research strategy can be employed. It involves utilising numerical simulations that are cost-effective and efficient to test and identify optimal designs. These designs can then be selected and utilised for creating prototypes. By leveraging these newly developed numerical models and established prototypes, the development process can be expedited while keeping costs low.

Objectives or project requirements

Reactors design and operation strategies are the critical step in new technology development, which determines the energy consumption and the whole stream efficiency. It is required to develop high-efficient reactors.

Process undertaken

The new models have been implemented in simulating and determining the lab-scale designs of these reactors. In this study, the lab-scale numerical model and the prototype will be scaled up with guidance from the numerical and experimental trials in the next stage.

Report 2: Waste PV module pyrolysis mathematical model and prototype development

Project Name: End-of-Life, highly efficient, low-cost and eco-friendly recycling technology for silicon photovoltaic panels

Knowledge Category:	**Technical**
Knowledge Type:	Technology
Technology Type:	Solar PV
State/Territory:	NSW

Key learning

A state-of-the-art computer model, reacting computational fluid dynamics and discrete element method (rCFD-DEM), was developed and coupled with a super-quadric model to explore the underlying mechanisms of heat and mass transfer behaviours during the waste PV particle pyrolysis process. This is the first time to incorporate the chip-like particle into the reacting flow system, which aims to more accurately describe the PV particle movement in the fluidised bed and fixed bed reactors. The optimal reactor operating conditions could be proposed based on the numerical models, and the design of the pyrolysis prototype is upgraded to further enhance the thermal delamination efficiency.

Implications for future projects

Based on the superquadric model in the rCFD-DEM framework and the established pyrolysis prototype, it will develop a novel multi-superquadric model to investigate the large-scale reacting system for waste PV panel recycling. With this model, the EVA removal in the sandwich structure PV particle can be simulated, which helps to optimise the pyrolysis conditions and thereby reduces the energy consumption for the thermal treatment stage.

Objectives or project requirements

Thermal delamination is the critical step in waste PV panel recycling, which determines the energy consumption and the whole stream efficiency. It is required to develop a high-efficient pyrolysis reactor to cost-effectively separate the glass and solar cells for the preparation of the next stage chemical leaching process. Taking advantage of the modelling method, the system design and operation strategies could be numerically examined and verified.

Process undertaken

The superquadric rCFD-DEM model has been implemented in simulating the chip-like PV particles' fluidisation and pyrolysis behaviours. In this study, the lab-scale numerical model and the prototype will be scaled up with guidance from the numerical and experimental trials in the next stage.

Report 3: The solar panel leaching process optimization in the stirring system using a combined experimental and numerical method

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Knowledge Category:	Technical
Knowledge Type:	Technology
Technology Type:	Solar PV
State/Territory:	NSW

Key learning

The study aims to optimise the leaching process of solar panels using a combined experimental and numerical method. A lab-scale prototype is built to demonstrate the metal leaching and also a leaching kinetics model is developed based on the experimental data. A reacting computational fluid dynamics and discrete element method (rCFD-DEM) is developed based on the kinetics model. The rCFD-DEM model helps to understand the fluid-solid interaction and mixing behaviour in the stirring system, which is critical for the leaching process. The study found that optimising the temperature and particle size can significantly improve the leaching efficiency of solar panels. The optimised process can help in the recovery of valuable metals such as Ag and minimize environmental impact.

Implications for future projects

The study provides valuable insights into the optimisation of the leaching process of solar panels, which can have important implications for future projects related to the recycling and recovery of valuable metals from electrical waste. The leaching kinetics model developed by the experimental study can be extended to other types of leaching processes. The use of CFD-DEM modelling in the study can be extended to other types of leaching processes to improve their efficiency and reduce environmental impacts. The findings can also help in the design of more efficient and cost-effective recycling processes for electrical wastes. Moreover, the study highlights the importance of recycling EoL solar panels to recover valuable metals such as silver, copper, and silicon, which can help in the development of a circular economy for solar panels. The findings of this study can be used to inform future policy decisions related to the management and recycling of end-of-life solar panels.

Objectives or project requirements

A lab-scale metal leaching prototype will be built to provide insight into the metal leaching process's detailed fluid-solid flow behaviours and find parameters that are important for the valuable metal leaching processes, helping the operators to select the optimal reactor operation strategies and designs. Predict metal leaching performance in a scale-up system cost-effectively and efficiently, aiming for the industrial-scale metal leaching reactor design.

Process undertaken

In this study, a lab-scale metal leaching prototype for demonstration is developed, and a combined CFD-DEM is developed to understand the fluid-solid interaction and mixing behaviour in the stirring system for determining the optimal parameters to improve the leaching efficiency of solar panels.

Report 4: Effective material separation by physical sieving-modelling assisted experimental study

Project Name: End-of-Life, highly efficient, low-cost and eco-friendly recycling technology for silicon photovoltaic panels

Knowledge Category:	**Technical**
Knowledge Type:	Technology
Technology Type:	Solar PV
State/Territory:	NSW

Key learning

This research targeted the issue of PV materials fragmentation after the delamination process and proposed a new separation technique for the effective separation and sorting of different PV materials. The proposed method is an optimisation of the conventional sieving technology, and it is developed for the recycling of wasted PV panels. Specifically, the conventional physical sieving process couldn't effectively separate glass and solar cell materials from the mixture, and adding the optimal sieving aids and adjusting the sieving machine conditions could achieve the objective that effectively separating the materials from the debris mixture resulting from the pyrolysis process. It is the most critical step that determines the energy costs in the subsequent chemical leaching process.

Implications for future projects

Compared with other separation methods that are currently in use for the recycling of waste PV panels and waste from electrical and electronic equipment (WEEE), such as density separation and electrostatic separation, the proposed sieving technology is a mechanical separation technique, and therefore, has a relatively lower operating cost and is easily applied for industrial operations. There is great potential on performing this new sieving technique at an industrial scale to optimise the recycling efficiency, reduce the operating cost, and enhance the recovery yield of metals, glass, and solar-grade silicon. One Australian Patent (AU2002903639) has been filed, which proposed a method and apparatus for separating photovoltaic module materials. The database of this experimental study, which summarise the designs and combinations of different sieving parameters including duration, amplitude, interval, and properties of sieving aids, can be valuable for the commercialisation of the proposed sieving technology and provides critical information for future modelling works.

Objectives or project requirements

The effective separation of solar cells and glass is a critical step that connects the thermal delamination and chemical leaching processes, which affects the final costs of the whole recycling system. The more concentrated solar cell could be collected and being subjected to the leaching reactor, the less acid and leaching time is required and that will also reduce the pressure of waste management. Therefore, the high-efficient separation apparatus and strategies are necessary to be developed in this project.

Process undertaken

The study is to understand the material separation mechanism during the physical sieving process. The modelling-supported experimental studies help to develop the advanced separation apparatus and operating conditions for further efficiency improvement in each step of the waste PV panel recycling system.