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Commentary on Technoeconomic Analysis of High-Value, Crystalline Silicon Photovoltaic Module Recycling Processes [Solar Energy Materials and Solar Cells 238 (2022) 111592]

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We disagree with the results presented in the paper "Technoeconomic Analysis of High-Value, Crystalline Silicon Photovoltaic Module Recycling Processes" which appeared in Solar Energy Materials and Solar Cells 238 (2022) 111592. It compared a recycling process we reported in a paper published in 2017, "Strategy and Technology to Recycle Wafer-Silicon Solar Modules" [1], with the Full Recovery End-of-Life Photovoltaic (FRELP) process funded by the European Union [2]. It concluded that the cost of running our process is twice as high and our revenue is 20% lower than the FRELP process. In this Commentary we would like to point out several misconceptions in the paper which led to the erroneous results.

There seems to be some consensus in the community that the recycling process for silicon panels involves two stages [1–4]:

- Physical disassembly to recover the bulky materials in silicon panels including the aluminum frame, copper wiring, and glass cullet.
- Chemical recycling to recover the metals in silicon cells including silver, lead, tin, copper interconnects, and silicon (either metallurgical grade or solar grade).

To link the two stages, a technology to gently and cleanly separate the silicon cells from the glass is needed. Candidates for this technology include infrared belt furnace heating coupled with knife cutting of the encapsulant [2], hot knife cutting of the encapsulant [5], or pyrolysis of the encapsulant as proposed over 20 years ago [6–8].

1. Panel disassembly

We have never performed any experiment on physical disassembly of silicon panels and reported no such result in the 2017 paper. It is surprising that the paper assigned a lower aluminum recovery rate for our panel disassembly process, 94% vs. 99.4% for the FRELP process, and a marginally higher glass recovery rate, 99% vs. 98% for the FRELP process. These arbitrary assignments of aluminum and glass recovery rates resulted in a \$0.11/panel lower revenue for our process than the FRELP process.

Table 1 lists the value of each material contained in a typical 60-cell silicon panel as of June 25, 2021 assuming metallurgical-grade silicon. The total revenue potential is \$10.40/panel if all the materials are recovered at the highest possible rates. By the arbitrary assignments of recovery rates, our process loses \$0.125/panel on aluminum and gains \$0.015/panel on glass, for a net loss of \$0.11/panel in revenue.

It should be noted that our paper focused on the chemical recycling process for silicon cells. Our cell recycling process works with any panel disassembly process, out there or to be developed. All our process requires is sheets of silicon cells cleanly separated from the glass. This means that our "panel disassembly process", if we had one, should have a similar revenue and cost to the same process performed by other entities. The cost of our FRELP panel disassembly process would never be twice as high as the original FRELP process.

2. Cell recycling

Our chemical cell recycling process and the FRELP process are similar:

- Both processes employ pyrolysis to remove the encapsulant from silicon cells.
- Both processes employ nitric acid for metal leaching.
- Both processes employ electrowinning for metal recovery from the leachate.

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Table 1
Potential revenue from a typical 60-cell silicon panel as of 6/25/2021, $10.40/panel assuming metallurgical-grade silicon.

Material	% Recovery	Weight	Price ($/kg)	Value	% Total
Glass	100	13.5 kg	0.10	$1.35	13.0
Al	100	1.83 kg	1.15	$2.10	20.2
Cu	100	0.11 kg	7.27	$0.80	7.7
Polymers	67	1.18 kg	n/a	0	0
MG-Si	100	0.62 kg	1.50	$0.93	8.9
Ag	100	6 g	840.02	$5.04	48.5
Pb	100	18.3 g	1.28	$0.02	0.2
Sn	100	21.9 g	7.16	$0.16	1.5

although there are small differences in concentration, time, temperature, etc.

2.1. Lead recovery

One major difference is that our process requires two-step sequential electrowinning. This is done on purpose to recover toxic lead from silicon panels. The FRELP process does not recover lead. As shown in Table 1, each panel contains ~15 g of lead. If landfilled, lead could leach out under acidic rain [9] or with acetic acid from the decomposition of the encapsulant. Our process recovers 99% of the lead. The extra cost for lead recovery, maybe 10% over the FRELP process, is well worth it.

The ~10% higher process cost is partially offset by the values of the additional metals our process recovers: tin, lead, and copper interconnects. This is another major difference between our process and the FRELP process. Based on Table 1, we estimate that the additional revenue from tin, lead, and copper interconnects is $0.35/panel over the FRELP process.

The chemical wastes from the two processes are different. The FRELP process generates a lead-containing waste, and additional steps with additional cost are required to remove lead from the waste. Our process recovers 99% of the lead, and extending the lead electrowinning time can bring the lead content to a safe level. With all the factors the two processes have a similar cost.

2.2. Silver and copper recovery

Our reported recovery rates for silver and copper are apparently lower than the FRELP process: 74% vs. 94% for silver and 83% vs. 97% for copper. It should be noted that determining the precise recovery rate of a metal is tricky. One can estimate the amount of silver, copper, lead, or tin in a silicon panel based on the current manufacturing processes, but there are variations and it is difficult to determine the exact amount of these metals in a panel. The situation becomes almost impossible with an end-of-life panel: no one knows the exact cell structure, panel structure, wafer thickness, silver content, lead content, etc. after 25 years with the manufacturer long gone. For these reasons we performed a controlled experiment: a known amount of a metal is dissolved in nitric acid and compared to the amount of the metal recovered to determine the recovery rate.

The fundamental reason for the low silver and copper recovery rates in our paper is in the chemical we chose for metal leaching, nitric acid, which is the most common leaching agent reported for silicon panels [1–4]. Electrowon silver and copper from a nitric leachate often have a dendrite morphology [1]. The long needles of silver and copper often detach from the cathode and fall to the bottom of the tank, where they are re-dissolved in nitric acid. This constant competition between electrowinning and re-dissolution results in low metal recovery rates. There are engineering solutions to prevent these detached metal needles from re-dissolution. The FRELP team may have employed such a solution for the high recovery rates reported. Nevertheless a precise value for the metal recovery rate is difficult for metals recovered from panels, as the exact amount of the metal in a panel must be determined first.

2.3. Silicon recovery

The final steps in our process is the recovery of solar-grade silicon, where the paper totally misrepresented our process. It assumed that recyclers would do all the steps designed for solar-grade silicon but would get paid for only the price of metallurgical-grade silicon. It is better to assume that recyclers would not do anything which is technically feasible but makes no financial sense for them.

The price for solar-grade silicon has skyrocketed in the last 12 months. As of June 25, 2021, the solar-grade silicon recoverable from a typical 60-cell silicon panel is worth $9.70/panel even if it can be sold only as second-grade solar silicon, which has a minimum purity of 6Ns. This increases the total revenue potential to $19.17/panel. If we count in the cost for solar-grade silicon recovery, we must count in the additional revenue generated by the recovered solar-grade silicon.

The cost for solar-grade silicon recovery turns out to be quite high due to the stringent purity requirements. TG Companies has first-hand knowledge as it developed a prototype tool for recovery of metals and solar-grade silicon from silicon cells. Metal recovery requires several tanks for leaching and electrowinning. Solar-grade silicon recovery requires ultrapure chemicals and water, multiple rinses, quick drying, and careful handling to prevent contamination. Besides cost, there are also difficulties in quality control. For example, if n-type panels and p-type panels are mixed, the recovered silicon automatically downgrades to metallurgical-grade silicon [4].

With all the difficulties involved in solar-grade silicon recovery, it is possible that metallurgical-grade silicon makes a perfect sense as the paper suggested. This leads to another misconception in the paper. The emitter and back-surface field do not qualify as solar-grade silicon. Only the base is solar-grade silicon and this is why the recovery rate of solar-grade silicon is limited to 90%. If the goal is metallurgical-grade silicon, the emitter and back-surface field can stay and the recovery rate is 100%. In fact if the goal is ferro-silicon, the recovery rate is 110%. Ferro-silicon requires a minimum of 75% silicon content. The silicon cells before any leaching has an 85% silicon content, so the non-silicon layers including back aluminum electrode, silicon nitride antireflection layer, copper interconnects can all stay and be sold as ferro-silicon. There are far fewer steps, thus much lower cost, in recovering ferro-silicon or metallurgical-grade silicon but the revenue from silicon is significantly lower [4].

2.4. The real issues

Our process or the FRELP process is by no means perfect. Some of the real issues are listed below, which are our current focuses in this project:

- Metal leaching with concentrated nitric acid releases nitrogen oxides. A scrubber is needed to capture the hazardous exhaust. This is true for both processes.
- The nitric acid is used only once and then becomes waste, so there is a large quantity of hazardous waste. This is true for both processes.
- The silver and copper recovery rates are low. The FRELP process has better recovery rates but there is still room for improvement.
- Our process recovers lead oxide, and additional steps are needed to obtain metallic lead. The FRELP process does not recover lead, so it requires a more complicated waste treatment process.

3. Summary

There are multiple misconceptions in the paper “Technoeconomic Analysis of High-Value, Crystalline Silicon Photovoltaic Module Recycling Processes” (Solar Energy Materials and Solar Cells 238 (2022) 111592) which led to erroneous results. A more objective comparison between our recycling process published in 2017 and the FRELP process for silicon panels suggests that the two processes have a similar cost and a similar revenue, within a few percentage points. However, our process recovers three metals the FRELP process does not: lead, tin, and copper interconnects. The recovery of lead is particularly important as it eliminates an environmental hazard and a liability for recyclers.

CRediT authorship contribution statement

M. Tao: Conceptualization, Funding acquisition, Methodology, Project administration, Supervision, Writing – original draft. **N. Click:** Formal analysis, Validation, Writing – review & editing, Data curation. **L. Ricci:** Data curation, Investigation, Methodology, Validation, Writing – review & editing, Formal analysis.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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