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Recycling of solar photovoltaic panels: Techno-economic assessment in waste management perspective

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ABSTRACT

This work assessed the economic sustainability of photovoltaic panels (PV) recycling. The PV throughout and silver (Ag) concentration in PVs are the main factor affecting recycling. For high Ag concentrations (0.2%), the recycling is sustainable without PV recycling fee if the PV throughput is higher than 18,000 t/yr. Lower processing volumes enable sustainability only with recycling fees from 0% up to 46% of the total annualized costs in the throughput range 18,000–9000 t/yr. For low Ag concentrations (0.05%) recycling fees are instead always needed to achieve profitability, unless the throughput is higher than 43,000 t/yr. Given the high Ag revenues, efforts should be done towards its recovery. If however a mixed silver-silicon fraction was sold for more than 50–70% of its actual value depending on the Ag concentration, a simplified process without hydrometallurgical separation could generate higher profitability on the short and long term. Given the decreasing Ag content in PVs, the profitability in recycling also depends on when the investments are realized. In the medium Ag concentration scenario and for Ag prices of 600 $/kg, PV fees are always required for the net present value (NPV) to be higher than CAPEX. The later the investment, the higher the PV throughputs and PV fees required to generate the same NPV. Investing in 2025 under the hypothesis of a regular loss scenario and an Ag price of 750 $/kg is the only condition that produces NPVs higher than CAPEX without PV fees if the throughput is at least 30,000 t/yr.

1. Introduction

In recent decades, photovoltaic (PV) panels became a reliable solution to transform solar energy in electricity (Tao and Yu, 2015). Among PVs, the technology based on crystalline silicon (Si-crystalline) currently covers over 90% of the global market (SPE, 2018) whereas alternative technologies based on Cd–Te and CIGS are relegated to minor roles.

In 2015, the installed PV capacity was 222 GW worldwide, and since then has been increasing at a rate of 20–30% per year up to reach the 594 GW in 2019 (Okoroigwe et al., 2020) and 700 GW in 2020 (Mahmoudi et al., 2020). As of 2022, the yearly installed PV capacity is expected to have reached the 1200 GW (Lu et al., 2019), with China owing more than one-third of the global PV installed capacity (Wang et al., 2022) and with the remaining two-thirds being distributed between USA, Europe and other Asian countries such as Japan and India (Gautam et al., 2021; Jain et al., 2022). Given the average PV lifetime of 25–30 years (Paiano, 2015), the cumulative global PV waste are also expected to increase from the 43,500–250,000 metric tons (t) of 2016 to over 70 million tons by 2050 (IRENA et al., 2016: Weckend et al., 2016).

Recycling this amount of EOL-PV panels waste is crucial to increase the sustainability of the entire solar energy sector from both economic and environmental points of view (Corcelli et al., 2017; Tao and Yu, 2015). This requirement has been formally recognized by the EU, who included the EOL-PV panels in the list of waste of electric and electronic equipment (WEEE) (European Parliament and The Council of European Union, 2012). Accordingly, specific minimum targets have been set for their collection, recycling and recovery. Starting from August 2018, collection, recycling and recovery must be at least 65%, 80%, and 85%, respectively. Therefore, the development and implementation of efficient and sustainable recycling processes is highly anticipated.

The key component in a crystalline-Si PV panel is the silicon-made photovoltaic cell, which also contains non-negligible amounts silver as electron coating metal for electrical connectors between the cells (Guo et al., 2021). The photovoltaic cell is typically encapsulated between

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two layers of ethylene vinyl acetate (EVA) and covered with glass on the front and a polyvinyl fluoride sheet on the back. Glass accounts for most of the photovoltaic panel weight (65–75%) whereas the EVA and the cell accounts for 7–15% and 1–2% of the PV weight, respectively. This module is mechanically supported by an aluminium frame, which accounts for about 10% of the PV weight (Granata et al., 2014). Silver (Ag) is present with extremely varying concentrations, which according to literature range from 10 to 600 mg/kg (Rubino et al., 2021), whereas copper and tin contribute to about 0.6% and 0.1% of the total weight, respectively (Gönen and Kaplanoğlu, 2019; Tao et al., 2020).

In this view, a suitable recycling technology must enable the cost-effective separation of the different materials in the panels and the extensive recovery of glass, silicon and metal components to sustain the economy of the process and limit the non-sustainable practice of land-filling (Deng et al., 2019). Recovering the valuable metals and in particular silver is however a challenging goal due to the presence of the encapsulating EVA polymer in between (Dias and Veit, 2018; Lunardi et al., 2018; Mahmoudi et al., 2019; Tao et al., 2020). Therefore, numerous research efforts have been made in the last decade in to develop efficient and sustainable recycling technologies (Klugmann--Radziemska, 2013; Klugmann-Radziemska and Ostrowski, 2010; Park and Park, 2014). These technologies can be generally divided in physical, thermal and chemical methods (Chowdhury et al., 2020). Among them, the *Advanced Photolife Process* (Pagnanelli et al., 2017a, 2017b, 2017a) enables over 80% materials recovery via integration of physical, thermal and chemical operations (Pagnanelli et al., 2019).

In a previous work, the *Advanced Photolife Process* was proven economically feasible (Rubino et al., 2020). However, the assessment was performed as a final stage in process development by assuming well-defined conditions (e.g. recycling volumes, concentrations) which is not meaningful in a broader waste management context. Many parameters possibly affecting sustainability are in fact unknown while others such as the compositions of manufactured PVs are expected to change through time (Corcelli et al., 2017; IEA-PVPS, 2018; IRENA and IEA-PVPS, 2016; Peeters et al., 2017). In this view, it is crucial to consider these parameters as variables in techno-economic assessments (TEA) to assess their effect on economic sustainability.

The goal of this work was then to identify the conditions for which PV recycling can be sustainable and/or profitable. Some of the questions that will be answered are as follows:

1. Can PV recycling be economically sustained by the sole process revenues? Or should recyclers receive recycling fees (hereafter referred to as *PV fee*)?
2. How does the Ag concentration in PVs affect sustainability? And what are the possible sustainable recovery strategies?
3. Given the decreasing Ag concentration in PVs, how sustainable are going to be future investments on PV recycling? How does the Ag price affect sustainability?

First, a multi-parametric analysis was performed by varying simultaneously the recycling fee and PV throughput of the developed process and by assessing their effect on economic outputs. Given the reported variability of Ag concentration in PV waste, this analysis was conducted for different Ag concentrations representing the low-end and high-end off the current Ag concentration variability. Following this operation, two process options of the recycling process (with and without hydrometallurgical recovery of silver and silicon) were analyzed to identify the trade-off conditions between the two possible investments. The PV-waste and Ag concentration trends were then forecasted for different hypothesis of scenarios in terms of PV waste generation and Ag concentration and integrated within a cash-flow analysis with variable cash-inflow to assess the profitability of investments in the time range 2025–2040 *via* determination of the net present value (NPV) of possible investments. Finally, the effect of the silver price on the economic feasibility was also assessed.

2. Methods

2.1. Process

The process analyzed in this work is referred to as *Advanced PhotoLife Process* (Fig. 1). In this process, the PVs are first removed of the Al frames and then grinded and sieved to liberate a fine-medium fraction (d < 3 mm) and a coarse fraction (d > 3 mm). The frames and the fine-medium glass are the first two process outputs (revenues) whereas the coarse glass is further processed to separate the different materials associated with it, namely polyvinyl fluoride backsheet, glass, EVA, silver, silicon, and a fraction named metal contacts that is composed of copper (84%), tin (11%), lead (2.5%) and aluminum (2.5%). This complex mixture is then contacted with cyclohexane, which weakens the EVA's binding ability to the point that the glass, polyvinyl fluoride and metal contacts can be liberated and separated by wet gravimetric separation with water. The cyclohexane suspension produced in the chemical conditioning is passed through a mesh sieve (7 mm) that retains the polyvinyl fluoride backsheet while allowing the under-sieve suspension to the wet gravimetric separation. In the wet gravimetric separation, the addition of water in volume ratio 1:1 to cyclohexane lets the EVA sheets and the Ag and Si therein contained float on the cyclohexane, which determines their separation from the top of the vessel. The coarse glass and metal contacts sink and are separated from the bottom of the vessel. The latest fraction is then passed through a 3 mm screen, which retains the coarse glass and metal contacts while letting the water-cyclohexane mixture through. The coarse glass and the metal contacts are then further separated by air classification, while water and cyclohexane pass through the screen and are separated *via* evaporation at 82 °C prior to recirculation upstream. The EVA residues containing the PV cell fragments are thermally treated at 650 °C to decompose the EVA polymer and liberate a residual ash fraction rich in silver and silicon. This fraction is treated hydrometallurgically by leaching, precipitation and thermal reduction. The leaching is performed at 60 °C for 2 h using 5 M HNO_3 (S/L ratio 1:3), which dissolves Ag as a nitrate while leaving Si undissolved in the residue. This residue is separated by filtration, thereby generating a metallurgical grade Si fraction that represents another revenue in the process. Silver is precipitated with sodium chloride (50 °C, 2 h) prior to reduction at 1000 °C with glucose as reducing agent and sodium carbonate flux (Sathaiyan et al., 2006). A detailed mass balance for the *Advanced Photolife Process* is reported in Table S1 and Table S2 (supplementary information) along with the specific process revenues. Among them, silver and silicon are separated-recovered hydrometallurgically and sold for their commercial price (Ag: 600 \$/kg; Si: 2.8 \$/kg). Copper and tin from the metal contacts are instead sold for 85% of their actual value (Cu: 8.5 \$/kg; Sn: 37 \$/kg) to compensate for the further processing required for their separation. Overall, the total recovered value accounts for 61 \$ per 100 kg of EoL PVs, which is somewhat similar to the 13.6 \$/m^2 of PVs reported in literature (Markert et al., 2020) given that 100 kg of PVs correspond to about 5 full panels of 1 m^2 each. The operating cost (OPEX), investment cost (CAPEX), and unit processing cost of the same process are reported in Table S3.

2.2. Process simulation

The process was simulated in a mixed batch-continuous mode using SuperPro Designer (Intelligen, Inc., USA). The chemical-hydrometallurgical operations were assumed to run in batch whereas thermal operations and frame separation were assumed to be continuous. The multi-parametric analysis was performed by simulating the process at different PV throughputs in the range 3000–30,000 t/yr, different PV recycling fees in the range 0–675 \$/t and different Ag concentrations in the range 0.05%, 0.2%. A second set of simulations was performed by progressively reducing the amount of Ag in the panels according to specific trend forecasts. These simulations were performed

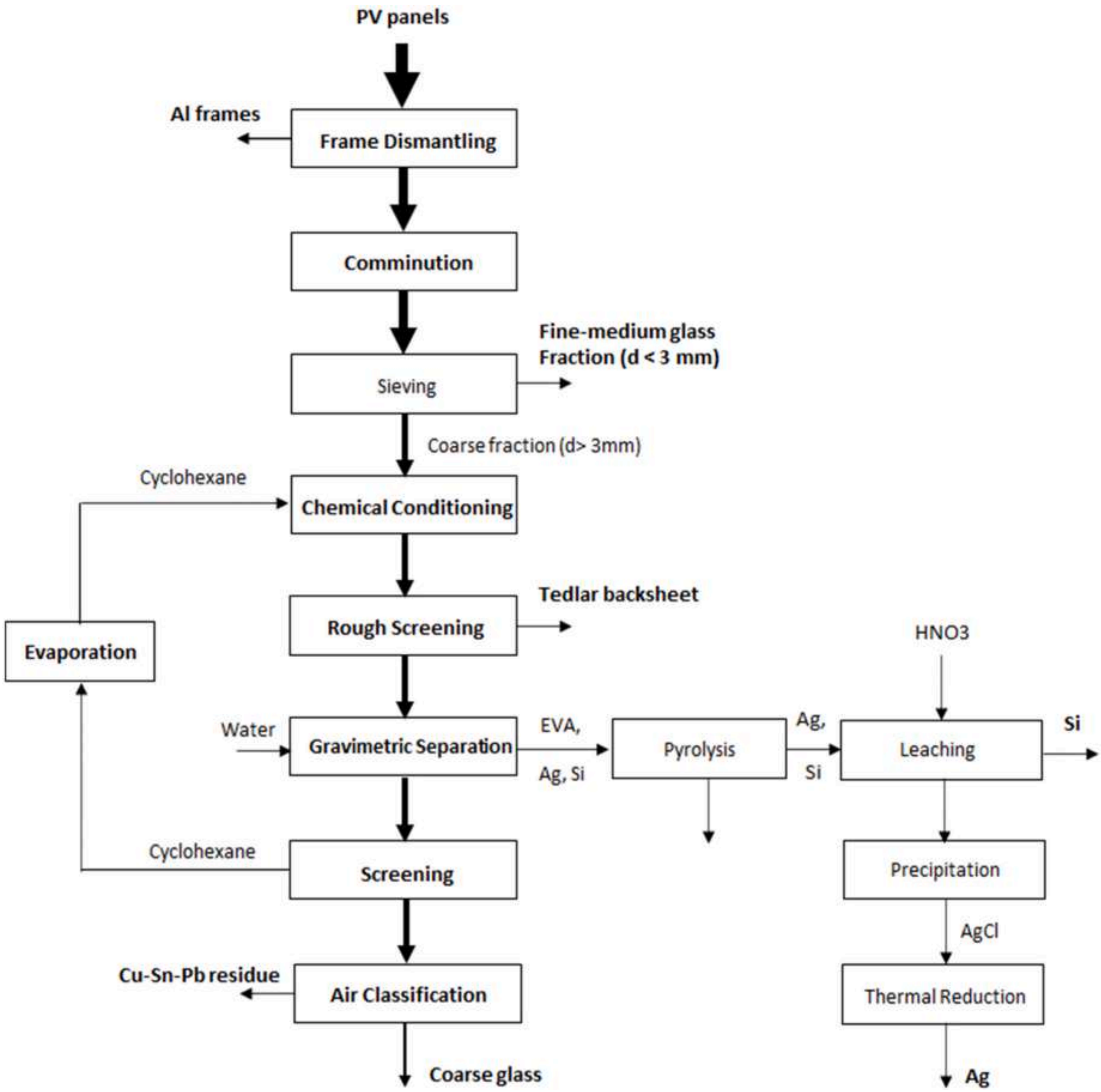

Fig. 1. Flow diagram of the *Advanced PhotoLife Process*.

based on the evolution of the Ag content in waste PV panels predicted with the methodology described in the supplementary information. This methodology enables to predict the Ag content in PV waste starting from the PV power installed during any year and the Ag content in the installed PV panels. In the present study, for the Ag content of manufactured PV panels, data corresponding to the medium scenario reported by (Peeters et al., 2017) were employed.

The mass balances related to frame dismantling, comminution, and sieving were obtained during the demonstration campaign of the *Photolife* project from 1 ton of mono, poly and amorphous Si-based panels as detailed in (Padoan et al., 2021); the mass balances for chemical conditioning, sieving, gravimetric separations, pyrolysis, and hydrometallurgical recovery were obtained from the pilot-scale mechanical treatment of two panels Si-mono (TOPCO Solar Module, TOPCO-230S6, 2011) and Si-polycrystalline (Sun Earth, TPB156X156-60-P 240, 2012) as reported in (Rubino et al., 2021).

2.3. Economics

The economic feasibility was assessed based on gross margin (GM), return on the investment (ROI), and net present value (NPV). The GM quantifies the portion of revenues that becomes gross profit, and it is calculated as in (1):

$$GM(\%) = \frac{Gross\ profit}{Revenues} \times 100 \tag{1}$$

where the gross profit is the difference between revenues and annual operating costs (AOC). The ROI quantifies the investment that can be paid back with 1 year profit (2):

$$ROI(\%) = \frac{Net\ Profit}{Total\ Investment} \times 100 \tag{2}$$

The NPV which represents the total value of future net cash flows (spread over the lifetime of a project), at the beginning of the project (3):

$$NPV = \sum_{t=0}^{T} \frac{Cf_t}{(1 + DR)^t} \tag{3}$$

with:

T: specific time within a project lifetime.
DR: discount rate.

Cf_t: cash flow at a specific time within the project lifetime.
T: project lifetime.

More detailed information on process economics can be find in the relevant literature (Peters and Timmerhaus, 1991).

2.4. Silver concentration forecast

The mathematical model used to predict the temporal evolution of the Ag concentration in EoL PV panels is described in the supplementary information. In what follows, we briefly summarize the main steps of the implemented procedure:

- The first step was to evaluate the temporal evolution of the installed PV power in the EU. Historical data on installed power were extracted from the EU Market Outlook reported in (SolarPower Europe, 2020) and employed for the period 2000–2020, while forecasts corresponding to the 'Medium Scenario' described in the same report were used for the period 2020–2024. For the periods 2025–2030 and 2031–2050, different compound annual growth rates (CAGRs) of installed power were estimated by imposing that the EU overall installed power $C_W(t)$ will be equal to 660 GW in 2030 (European Commission, 2021) and 1.94 TW in 2050.
- The amount of installed PV panels was computed by multiplying the installed power (MW) times the mass per unit power (ton/MW). The evolution of the mass per unit power was taken from (Peeters et al., 2017).
- The amount of EoL PV panels, and their Ag content, was computed for any year from the evolution of the amount of installed PV panels and from their Ag concentration (Peeters et al., 2017) using the Weibull lifetime distribution. This distribution quantifies the fraction of panels installed at time t_0 at any time $t > t_0$. Based on (IRENA and IEA-PVPS, 2016), both a regular loss scenario and an early loss scenario (increase in early failures) were considered.

Additional references related to the model description are: (European Commission, 2021; SolarPower Europe, 2020; Viebahn et al., 2015; Zimmermann, 2013).

3. Results

3.1. General economic feasibility

The results of the multi-parametric analysis ROI *vs* PV throughput and PV fee are shown in Fig. 2a and b for the Ag concentrations of 0.05% and 0.2%, respectively. The Ag concentration of 0.05% corresponds to the one found in the PVs during the experimental stage of the process development (Rubino et al., 2021). The Ag concentration of 0.2% is instead the one that according to manufacturer's data (IRENA and IEA-PVPS, 2016) is associated with PVs manufactured in the early 2000s and that, assuming a typical PV life of 20 years, should currently be contained in PV waste streams. It is worth remarking once more that the PV fee represents the money to be paid to recyclers to sustain the process. As this amount depends on specific agreements between the different stakeholder involved in PV recycling, it is unknown and is thus treated as a variable to assess the conditions for which it is actually required.

When the Ag concentration is 0.05% (Fig. 2a), the minimum PV recycling capacity to attain a positive ROI is 18,000 t/yr on the condition that the PV few is at least 525 $/t. However, under this condition the ROI is only slightly positive (6.9%), which does not correspond to an attractive condition. Processing a lower amount of PV panels would require PV recycling fees higher than 675 $/t, which is an unlikely condition given the current recycling scenario. In contrast, recycling 30,000 t/yr of PVs would ensure positive ROIs under most of the simulated conditions as long as the recycling fee is at least 150 $/t.

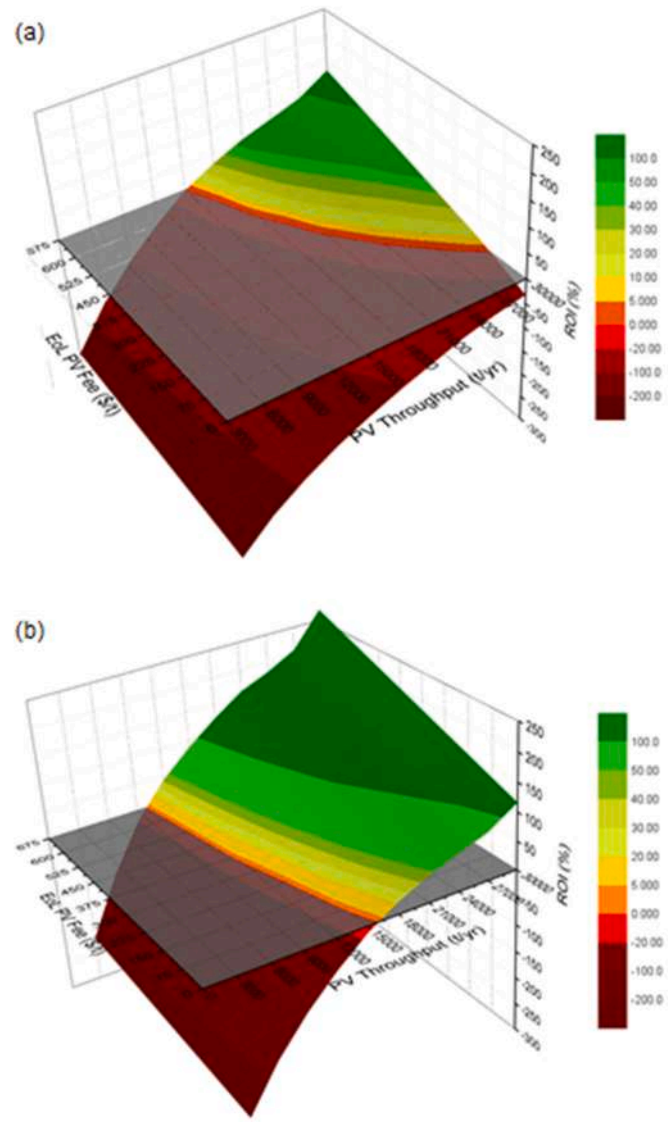

Fig. 2. ROI *vs* recycling fee and PV throughput for (a) Ag concentration 0.05% and (b) Ag concentration 0.2%.

Achieving attractive ROIs of about 20% requires instead processing 21,000–30,000 t/yr of PVs and collecting recycling fees of 425-225 $/t, respectively.

For Ag 0.2%, positive ROIs can already be obtained by recycling 12,000 t/yr if a PV fee of at least 375 $/t is paid to recyclers. ROIs of about 20% can instead be obtained at this recycling volume with a PV fee of about 500 $/t. Having recycling volumes equal or higher than 18,000 t/yr enables ROIs higher than 20% even without any recycling fee.

To evaluate the influence of the PV fee in a more general PV waste management context, a new quantity called PV fee index was introduced. The PV fee index is the total annual revenues from the PV fee (RFY) generated in a specific process normalized by the total annual cost (TAC) associated with the process, which is composed of the total investment cost (CAPEX) spread over the years of the project and the annual operating costs (OPEX) as in (4):

$$PV\ fee\ index\ (\%) = \frac{RFY}{\frac{CAPEX}{20} + OPEX} \times 100 \qquad (4)$$

This PV fee index was evaluated at different recycling volumes in the range 9000–30,000 t/yr and for variable PV fees in a the range 0–675

$/t to identify for each recycling volume the PV fee index that generates a 20% ROI, namely *critical PV* fee *index*. The results of these simulations are shown in Fig. 3. The regression parameters of the lines in Fig. 3 can be found in Table S4.

For Ag 0.2%, ROIs of 20% can be obtained with or without PV fee depending on the recycling volume. An extrapolation from the 0.2% Ag line suggests that if the PV throughput is lower than 17,935 t/yr, a recycling fee is always required to obtain the 20% ROI. This fee corresponds to PV fee indexes that increase constantly from 0% at the critical PV throughput of 17,935 t/yr up to 46% when the recycling volume is 9000 t/yr. Given the CAPEX and OPEX associated with this process capacity, these critical PV fees correspond to 0 $/t to 973 $/t in the same range. The extrapolation from the line 0.1% Ag highlights instead that the critical PV fee index becomes 0 when the recycling volume reaches 28,071 t/yr. Accordingly, ROIs of 20% can be generated by recycling larger volumes even without PV fees, or by recycling smaller volumes with linearly increasing PV fee indexes. For instance, when the recycling volume is 18,000 t/yr, the 20% ROI can be attained only with a PV fee index of about 18%, which given the related CAPEX and OPEX corresponds to 398 $/t of PV waste. For Ag 0.05%, a recycling fee is always needed to achieve 20% ROI as long as the recycling volume is lower than a critical value of about 43,000 t/yr. In this case, the PV fee index varies from 27% to 52% in the range 30,000–18,000 t/yr and can be predicted from the 0.05% Ag line for recycling volumes out of this range. Given the CAPEX and OPEX, PV fee indexes of 27–52% correspond to PV fees in the range 200–600 $/t of PV waste, respectively.

The relationship between critical PV fee index at Ag concentration at different recycling volumes is shown in Fig. 4. The equations of the fitting lines and related fitting parameters can be found in Table S5. Fig. 4 can be used to predict the critical Ag concentration below which the ROIs of 20% can be achieved only by receiving PV fees, and thus the required PV fee index.

For recycling volumes of 12,000–15,000 t/yr and Ag concentration in the range 0.05–0.2%, a PV fee is always required to attain ROI 20%. The required PV fee index ranges from a minimum of about 15% (15,000 t/yr; 0.2% Ag) to a maximum of 66% (12,000 t/yr; 0.05% Ag), which correspond to PV fees of 505 and 1090 $/t, respectively. Recycling any amount of PV waste between 12,000 and 15,000 t/yr without PV fee, the required Ag concentrations to achieve ROI 20% are extrapolated as 0.33% and 0.25%, respectively. ROIs of 20% can instead be achieved in the Ag concentration range 0.05–0.2% for any PV throughput equal or higher than 18,000 t/yr. Fig. 4 also highlights that the Ag concentration affects the PV fee index more at higher recycling volumes (increasing slopes). Given the higher intrinsic Ag value as compared to the PV fee, recycling more PV panels produces larger

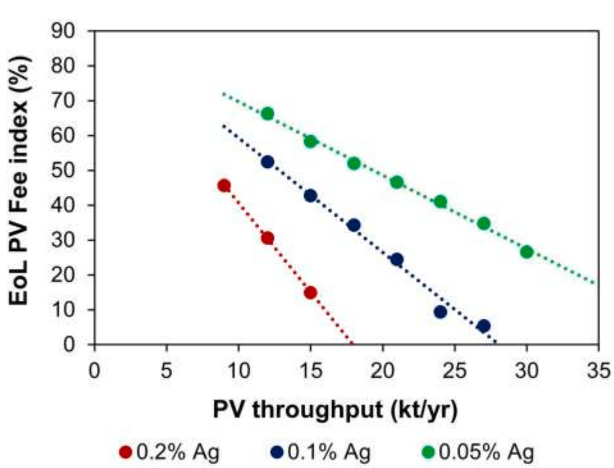

Fig. 3. Critical PV fee index (normalized PV fee normalized that produces 20% ROI) *vs* recycling volumes at different silver concentrations.

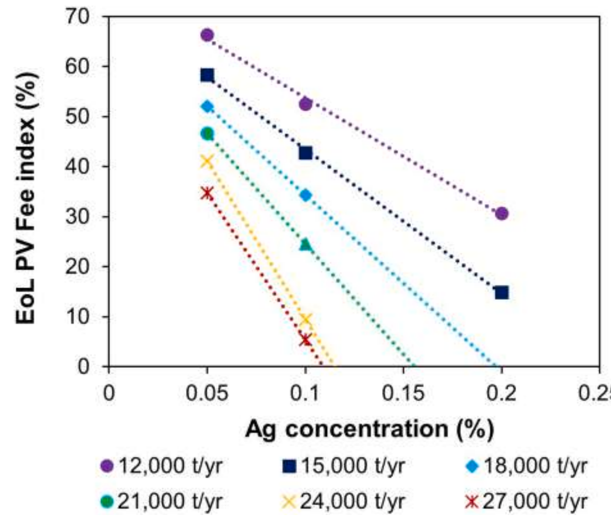

Fig. 4. Critical PV fee indexes (normalized PV fee normalized that produces 20% ROI) vs Ag concentration at different recycling volumes.

amounts of high-value revenues. This aspect is more explicitly evidenced in Fig. 5, where the revenues from Ag, and Cu–Sn at different Ag concentrations and PV throughputs are compared with the ones from the PV fees required achieve 20% ROI.

For Ag 0.05%, the revenues from the PV fee that grants the 20% ROI (critical PV fee) are 1.3–5.5 larger than the one from Ag in the PV throughput range 12,000–27,000 t/yr. In contrast, the revenues from Ag are 2–4 times the ones from the critical PV fee when the Ag concentration in PVs is 0.2% in the PV throughput range 12,000–15,000 t/yr (at PV throughput 18,000 t/yr the PV fee required to achieve 20% ROI is already negative because the recycling produces ROI higher than 20% even without PV fee). For Ag 0.1%, the revenues from Ag become higher than the critical PV fee from the recycling volume of 18,000 t/yr. Interestingly, the revenues from Cu and Sn together are 1.7–6.3 times lower than the ones from Ag in the concentration range 0.05–0.2%.

3.2. Strategy in silver recovery

While recovering silver is crucial to achieve economic sustainability, providing the recycling plant with a hydrometallurgical section adds extra complexity (i.e., increased CAPEX and OPEX, additional competences, environmental permits). This raises some questions: is the hydrometallurgical recovery of high-grade Ag really necessary? Or, could it be more convenient to sell for a lower price the Ag-rich material obtained after thermal EVA decomposition? Are there any conditions for which selling the Ag-rich material is economically more convenient?

Fig. 6 plots the selling prices of the Ag–Si mixture for which the two process options (with and without hydrometallurgical recovery) yield the same ROIs, namely *ROI-critical selling price*. These prices were obtained from the intersections of the curves ROI *vs* Ag selling prices in Figs. S1 and S2, which are also explained as supplementary information.

For Ag 0.2%, the ROI-critical selling price ranges from 12.2 $/kg without PV fee to 3.7 $/kg when the PV fee is 675 $/t. Accordingly, if the Ag–Si mixture was sold for higher prices the process without Ag hydrometallurgical recovery would result in a higher ROI. In contrast, the ROI-critical selling prices for Ag 0.05% range from 9.4 to 5.0 $/kg in the same PV fee range. It must be however remarked that the ROI-critical selling prices in the low Ag scenario actually correspond to higher to larger portions of the actual Ag–Si value in the specific fraction. For instance, the selling price of 9.4 $/kg (Ag = 0.2%, PV fee 225 $/t) corresponds to 28% of the total Ag and Si value contained in the ash from EVA decomposition (the fraction contains 33.75 $/kg worth of Ag and Si if sold for their commercial prices). In contrast, the slightly higher

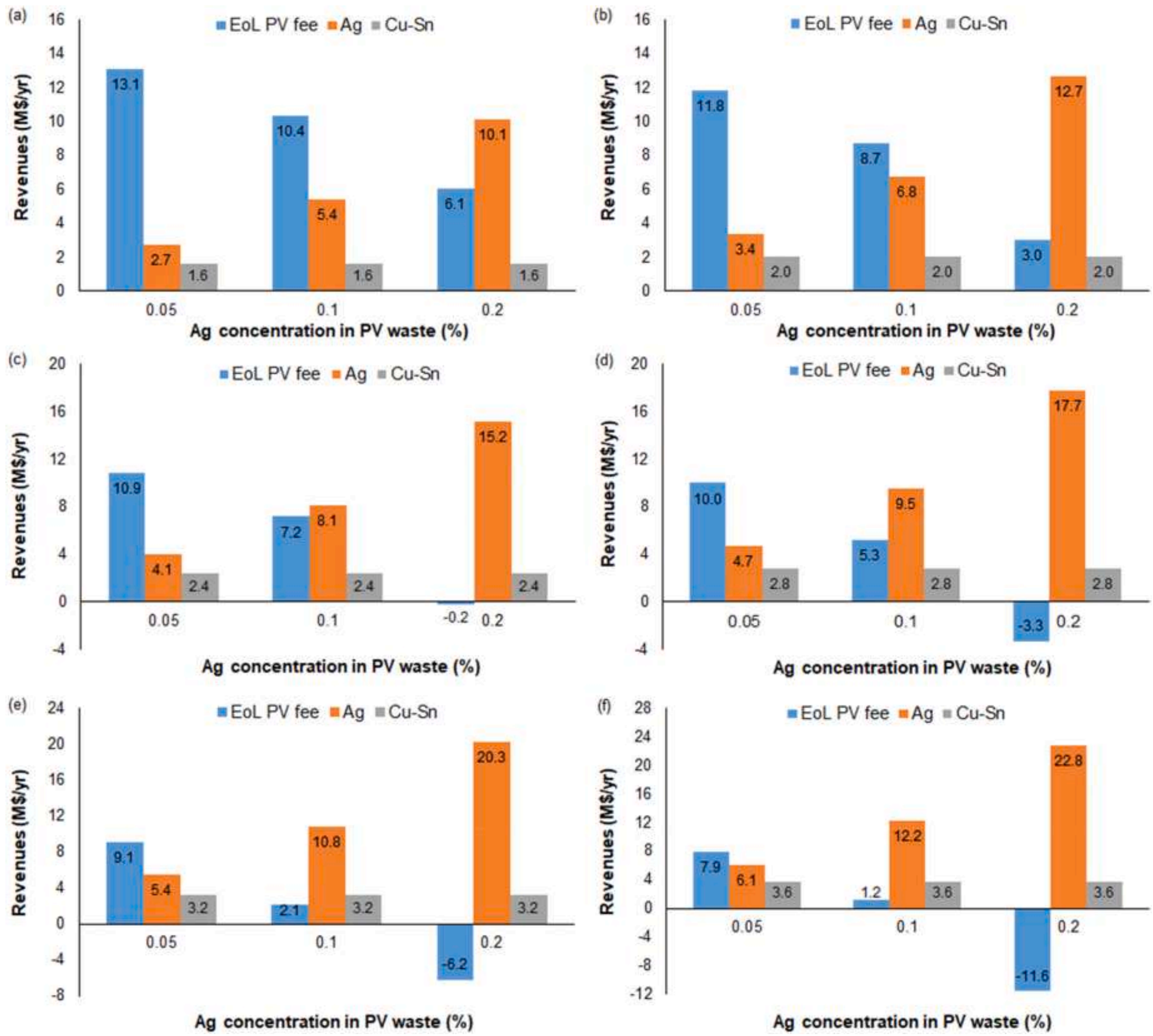

Fig. 5. Contribution of different recovered fractions to the total revenues required to achieve 20% ROI at different recycling volumes (a) 12,000 t/yr, (b) 15,000 t/yr, (c) 18,000 t/yr, (d) 21,000 t/yr (e) 24,000 t/yr, (f) 27,000 t/yr.

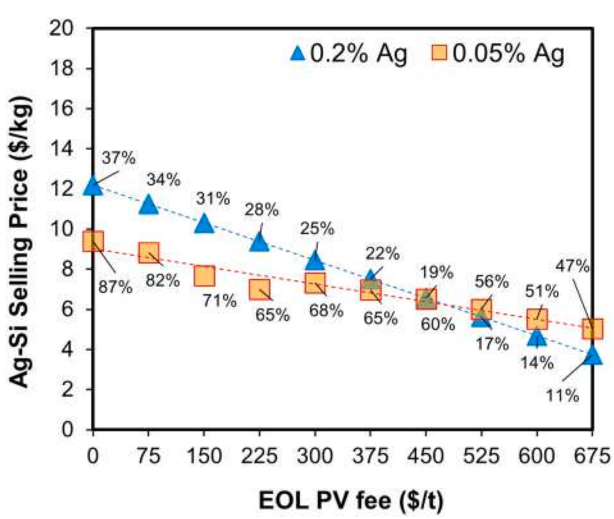

Fig. 6. Selling prices of Ag–Si mixture for which the processes with and without hydrometallurgical recovery (PV throughput 30,000 t/yr) result in the same ROI. (The labels in the figure represents the portion of actual value contained in the mixture material).

selling price of 8.8 $/kg (Ag = 0.05%, PV fee 75 $/t) corresponds to 82% of the total material value in the mixture (the total actual metal value in the same fraction is 10.8 $/kg).

While the ROI reveals what portion of the investment can be paid back with 1 year worth net profit, it does not specify how profitable the investment is after paying the investment back. A better measure of this aspect is the GM. Fig. 7 plots then the selling prices of the Ag–Si mixture for which the two process options yield the same GM, namely GM-critical selling prices. The data in Fig. 7 were obtained from the intersections of the curves in Figs. S3 and S4.

For Ag 0.2%, if the Ag–Si mixture was sold for more than for 15.2–17.0 $/kg (45–50% of the total actual value), the process without hydrometallurgical recovery would produce higher GMs. For Ag 0.05%, the GM-critical selling prices vary instead from 4.8 to 6.6 $/kg in the PV fee range 0–675 $/t. Accordingly, if the Ag–Si mixture was sold for higher prices, the process without hydrometallurgical recovery would produce higher GMs and would thus be more advantageous on the long term. Given the lower Ag concentration, this lower selling price actually corresponds to a higher relative value, namely 44–61%. It must be however remarked that for Ag 0.05% the process would not be economically feasible for PV fees up to 150 $/t.

The profitability on the short term (higher ROI) and long term (higher GM) of the two process options are graphically presented in Fig. 8a–b for Ag 0.2% and 0.05%, respectively. The profitability areas in

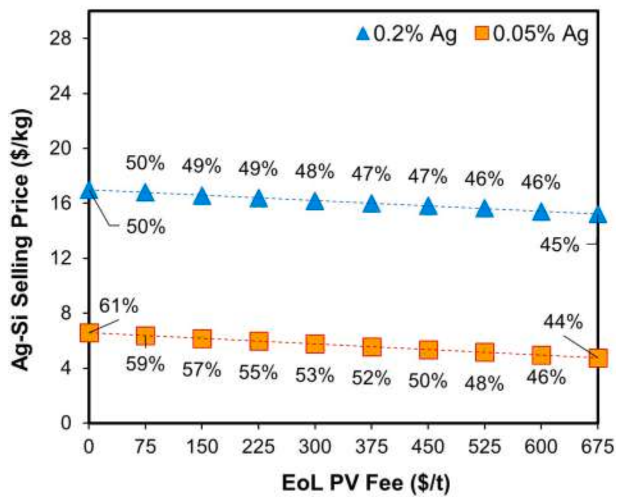

Fig. 7. Selling prices of Ag–Si mixture for which the processes with and without hydrometallurgical recovery (PV throughput 30,000 t/yr) result in the same GM. (The labels in the figure represents the portion of actual value contained in the mixture material).

these figures are delimited by the lines in Figs. 6 and 7. Fig. 8 can be used to predict the conditions for which selling the Ag–Si mixture is more/less profitable then selling higher grade Ag and Si for upon (hydro)metallurgical processing. For Ag 0.2%, the (hydro)metallurgical recovery is more profitable on the short and long term if the Ag–Si is sold for less than 12–36% of its actual value in the PV fee range 675-0 $/t (Fig. 8a, green area). Selling the Ag–Si rich fraction becomes more profitable on the short and long term if the Ag–S can be sold for more than 45–50% of its actual value in the PV fee rang 675-0 $/t (Fig. 8a, red area). For any situation in between (Fig. 8a, white area), selling the Ag–Si rich fraction is more profitable only on the short term. For Ag 0.05%, selling the Ag–Si rich fraction becomes more profitable on the short and long term only for relatively higher values, namely 75-48% of the actual metal value in the PV fee range 150–675 $/t (Fig. 8b, red area). In contrast, selling the Ag–Si rich fraction would be less profitable on the short and long term if this fraction was sold for less than 57-44% of its actual value in the PV fee range 150–675 $/t (Fig. 8b, green area). In this case however, any selling price in between would determine a situation in which selling the Ag–Si rich fraction would be more profitable on the short term but not on the long term (Fig. 8b, white area).

3.3. Sustainability with decreasing Ag content and variable Ag price

How does the Ag trend affect the attractiveness of investments in PV recycling? Given the decreasing Ag concentrations in PVs, will there be a time when investments on recycling won't be profitable anymore? These questions were answered through a cash flow analysis where the annual cash flows decreases progressively along with the Ag concentration in PVs. This requires knowing the evolution of the Ag concentration in manufactured PVs and the PV life time distribution. The evolution of the mass of PV waste and their Ag content as predicted over the period 2000–2050 is reported in Fig. 9.

Variations are apparently induced by an increase in the shape factor α from 2.5 (early loss scenario) to 5.4 (regular loss scenario). Lower values are invariably found for the mass of EoL c-Si panels with $\alpha = 5.4$ as compared to $\alpha = 2.5$. This can be explained by noticing that with $\alpha = 2.5$, there is an increased number of failures occurring before the characteristic lifetime of 30 years, and thus a larger fraction of the panels installed in 2010–2020 reaches end-of-life before 2050. The shape factor α produces an opposite effect for the evolution of the Ag fraction in PV waste (Fig. 9b). Here, increasing α has the effect of increasing the Ag concentration. This can be explained by noticing that the Ag fraction has

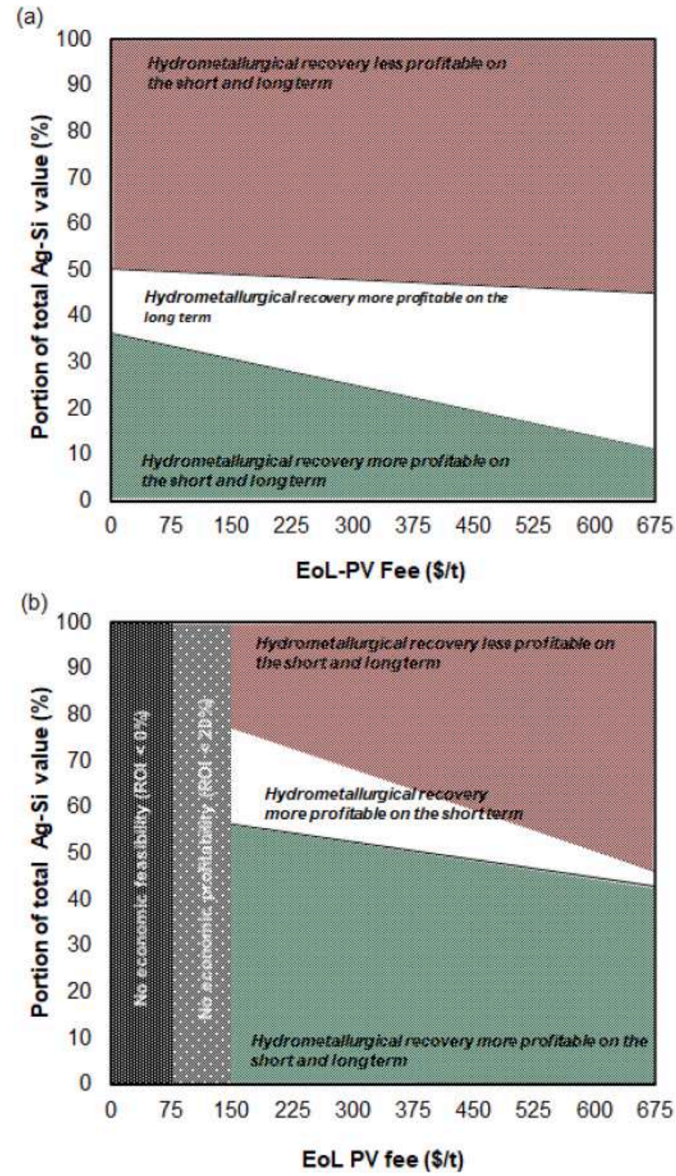

Fig. 8. Profitability of the two process options on the short term and long term based on the breakeven ROI and gross margins for (a) 0.05% Ag and (b) 0.2% Ag (PV throughput = 30,000 t/yr).

been continuously decreasing between 2000 and 2020, and it is predicted to become negligible within 2030. This determines the lower average Ag fraction in the waste PV panels described in Fig. 9b. The difference in Ag fraction determined by variations in α is lost starting from years close to 2050, when a negligible Ag content is found in the dismissed panels.

It should be remarked that the reliability of the proposed predictions decreases as the upper bound of considered time window is approached. In particular, while the assumption of an installed power of 660 MW in 2030 is considered realistic, larger uncertainty is associated with the assumption of 1.94 TW in 2050. On the other hand, it should be remarked that the focus of the present analysis is to estimate the evolution of the mass of silver that can be recovered from EoL PV panels. This mass will become progressively negligible in PV panels installed after 2030, and thus even large deviations between the predicted and the actual installed power after 2030 will barely affect the outcomes of the evaluation.

These data were used to perform the cash flow analysis with time-variable Ag concentration and determine the NPV of investments on

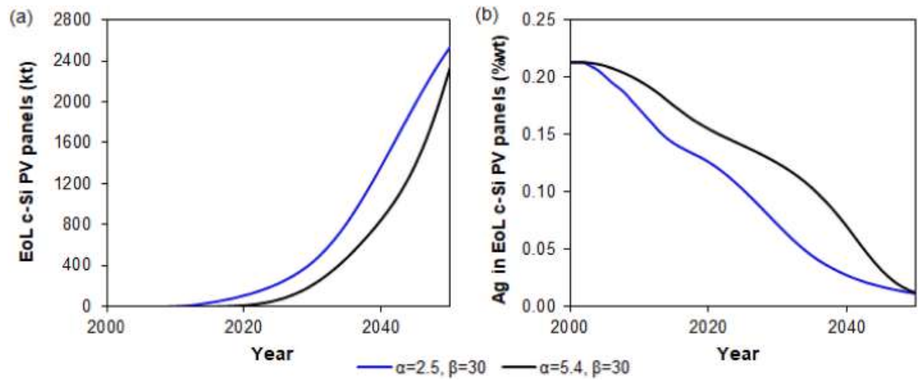

Fig. 9. Evolution of the amount of waste c-Si PV panels (a) and related Ag concentration during the period 2000–2050 (b) under the hypothesis of regular loss scenario (α = 5.4, β = 30) and early loss scenario (α = 8.7, β = 30).

PV recycling project performed between 2025 and 2040. The financial conditions assumed in the cash-flow analysis are listed in Table 1.

Since the profitability of investments in PV recycling projects strongly depends on recycling volumes, the cash flow analyses were performed at different PV throughputs. Given that however only positive NPV were obtained only for high recycling volumes, the results of the cash flow analysis are shown in Fig. 10 only for the PV throughputs of 30,000 t/yr and 27,000 t/yr. In these simulations, the PV fees were also varied in the range 0–525 t/yr to assess whether suitable NPVs can be obtained without PV fees and, if not, the PV required to attain profitability.

For a better comparison across different recycling technologies, the PV recycling fees used in this analysis was also normalized by the TAC and unit processing cost (UPC) (Table 2).

As a general trend, the sooner the investment, the higher the profitability. However, under none of the simulated conditions (Fig. 10) the decreasing Ag trend will result in positive NPVs without PV fees. Processing 30,000 t/yr of PVs under the assumption of regular loss scenario (Fig. 10a) produces NPVs higher than the CAPEX only for early investments (2025) and as long as the PV fee is at least 150 $/t. Later investments will otherwise be profitable only for higher PV fees. Under the assumption of early loss scenario (Fig. 10c), the NPVs are tendentially lower under the simulated range. Here, NPVs higher than CAPEX can be attained only if the PV fee is at least 375 $/t as long as investments are done by 2025. Processing lower amounts of EoL PVs expectedly results in even lower NPVs. Producing NPVs higher than CAPEX when processing 27,000 t/yr of PVs requires PV fees of at least 225 $/t in case of regular loss scenario (Figs. 10b) and 450 $/t in case of early loss (Fig. 10d). Investing on this recycling volume will however not be profitable anymore from 2040 regardless of the loss scenario in the simulated PV fee range.

Along with the Ag concentration, the Ag price is also expected to play a crucial role in determining the sustainability of PV recycling. In this view, whereas the average Ag price between 2014 and 2020 was about 600 $/kg, a sharp and dramatic price increase up to a new average of 750 $/kg was observed from the second half of 2020 (LME, 2022). How does this development affect the profitability in PV recycling? To answer this question, the simulations presented in Fig. 10 were repeated by increasing the Ag price from 600 $/kg to 750 $/kg. The results are gaphically summarized in Fig. 11. The results for the whole set of simulations are instead listed in Tables S6–S9 along with results from additional simulations under the hypothesis of a high Ag concentration scenario (results not addressed here).

An increased Ag price of 750 $/kg produces comparatively higher NPVs, which was clearly expected. In this case however, an early investment (2025) on high recycling volumes (30,000 t/yr) produces under the hypotesis of a regular loss scenario an NPV higher than CAPEX (13.4 M$ vs 10.1 M$) even without PV fee (Fig. 11a). Yet, the same conditions under the hypothesis of early loss scenario generates an NPV higher than CAPEX only for a PV fee of 300 $/t (Fig. 11c). The NPV at lower recycling volumes (27,000 t/yr) decreases significantly regardless of the loss scenario. In the hypothesis of a regular loss, an NPV of about 7 M$, corresponding to about 70% of the CAPEX, can be obtained by adopting a PV fee of 75 $/t; doubling this fee to 150 $/t generates instead an NPV of about 20 M$ (Fig. 11b).

Overall, increasing the Ag price from 600 $/kg to 750 $/kg in the medium concentration scenario produces an average effect on the NPV that was quantified as +8.75 M$ (Tables S6–S9). The same change in the high Ag concentration scenario determines instead an increase in the average NPV up to 11.7 M$. Finally, moving from a medium Ag concentration scenario to a high Ag concentration produces an increase in the average NPV from 10 M$ to 15 M$ and results in NPVs higher than CAPEX even without fee for both simulated Ag prices as long as the assumption of regular loss scenario is mantained and large throuhgputs (30,000 t/yr) are considered (Tables S8–S9).

Table 1
Financial conditions assumed in the cash-flow analysis.

Duration of the project	20 years
Income tax	25%
Construction & start-up time	34 months
Depreciation calc. method	Linear
Depreciation time	10 years
Salvage value	5%
DFC repartition	3 years
DFC repartition proportion	30-40-30%
Inflation rate	4%
NPV interest	7%

4. Discussion

The economic sustainability in PV recycling is a trade-off between process cost and revenues produced. It thus depends on recycling volumes, recovery rates, and commercial value of the recovered materials. Among valuable fractions, Ag, Cu, Si, and Sn are the most valuable materials to target for recycling. This is particularly true for Ag, which exhibits the lowest concentration but 500 to 800 times the value of Sn and Cu, respectively. The Ag revenues are in fact always higher than the ones from Cu–Sn, even if the Ag concentration in PV waste is the lowest in our simulations (0.05%). Therefore, investments on Ag recovery are crucial to achieve profitability when the Ag concentration is at least 0.1%. For lower Ag concentrations such investments contribute less to profitability at low recycling volumes but can still contribute significantly at high recycling volumes, when the ratio PV fee/Ag becomes slightly higher than 1. Although the Ag separation and recovery is crucial for profitability, selling a Ag–Si rich fraction could be even more profitable on the short and/or long term depending on the selling price

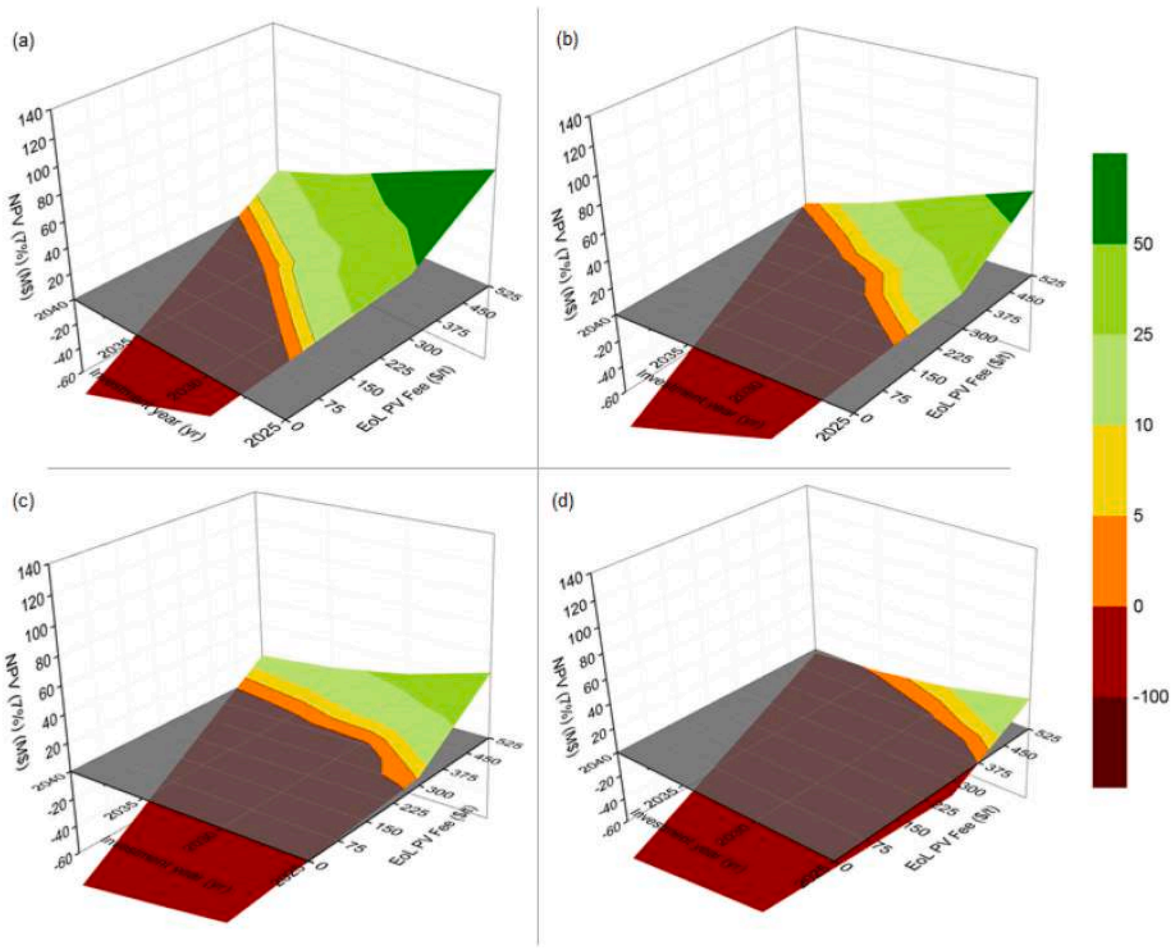

Fig. 10. NPV of different investments between 2025 and 2040 under the assumption of medium Ag concentration scenario: (a) PV 30,000 t/yr, regular loss (α = 5.4), (b) PV 27,000 t/yr, regular loss (α = 5.4), (c) PV 30,000 t/yr, early loss (α = 2.5), (d) PV 27,000 t/yr, early loss (α = 5.4). (Ag price: 600 $/kg).

Table 2
Simulation conditions and their relationship with the PV fee index and unit processing cost.

PV throughput (t/yr)	TAC ($/yr)	PV fee ($/t)	Revenues PV fee ($/yr)	PV fee index (%)	Fraction of UPC (%)
30,000	22,802,855	75	2,250,000	9.9	10.0
		150	4,500,000	19.7	20.0
		225	6,750,000	29.6	30.0
		300	9,000,000	39.5	40.0
		375	11,250,000	49.3	50.0
		450	13,500,00	49.2	60.0
		525	15,750,000	69.1	70.1
27,000	22,600,772	75	2,025,000	9.0	9.2
		150	4,050,000	17.9	18.3
		225	6,075,000	26.9	27.4
		300	8,100,000	35.8	36.6
		375	10,125,000	44.8	45.8
		450	12,150,000	53.8	54.9
		525	14,175,000	62.7	64.1

of this material. For Ag 0.2%, this trade-off price corresponds to about 50% of the actual material value in the Ag–Si fraction. This is due to the fact that selling the Ag–Si fraction would also enable to save on CAPEX and OPEX from the hydrometallurgical section of the plant. For Ag 0.05% however, the hydrometallurgical Ag extraction and recovery might enable higher ROIs, but lower GMs, unless the material is sold for 47–70% of its actual value depending on the PV fee. Clearly, larger Ag concentrations allow recyclers to compromise more on the selling price while keeping the same profitability.

The PV fee also plays a crucial role on sustainability/profitability. Lower PV throughputs and lower Ag concentrations reduce potential revenues up to the point that recycling cannot be economically sustained by selling the recovered materials. In these cases, recyclers will need to receive a recycling fee (PV fee). When the Ag concentration in PVs is between 0.05% and 0.2%, suitable ROIs (>20%) can be attained without any PV fee only if recycling volumes are at least 43,000–18,000 t/yr of PV waste.

Given the decreasing Ag concentration in PVs, the profitability of recycling also depends on when investments are realized. Under the hypothesis of a medium Ag concentration scenario and for Ag prices of 600 $/kg, PV fees are always required for the NPV to be at least equal to the CAPEX. The later the investment, the higher the PV throughputs and PV fees required to generate the same NPV. Investing in 2025 under the hypothesis of a regular loss scenario and given the current Ag price of 750 $/kg is the only condition that in our simulations results in NPVs higher than CAPEX even without PV fees if the recycling volumes is at least 30,000 t/yr.

Early research highligted the non-profitability of PV recycling as compared with landfillig (Cucchiella et al., 2015; McDonald and Pearce, 2010), which is however not a solution for obvious environmental reasons (Sharma et al., 2021). Other research suggested that PV recycling might be economically sustainable for PV throughputs higher than 20, 000 t/yr (Choi and Fthenakis, 2014; Deng et al., 2019). Our results also highlight economic sustainability for high recycling volumes and medium-to-high Ag concetrations in PVs (0.1–0.2%), and confirm that the economic profitability is strongly related to the presence of valuable

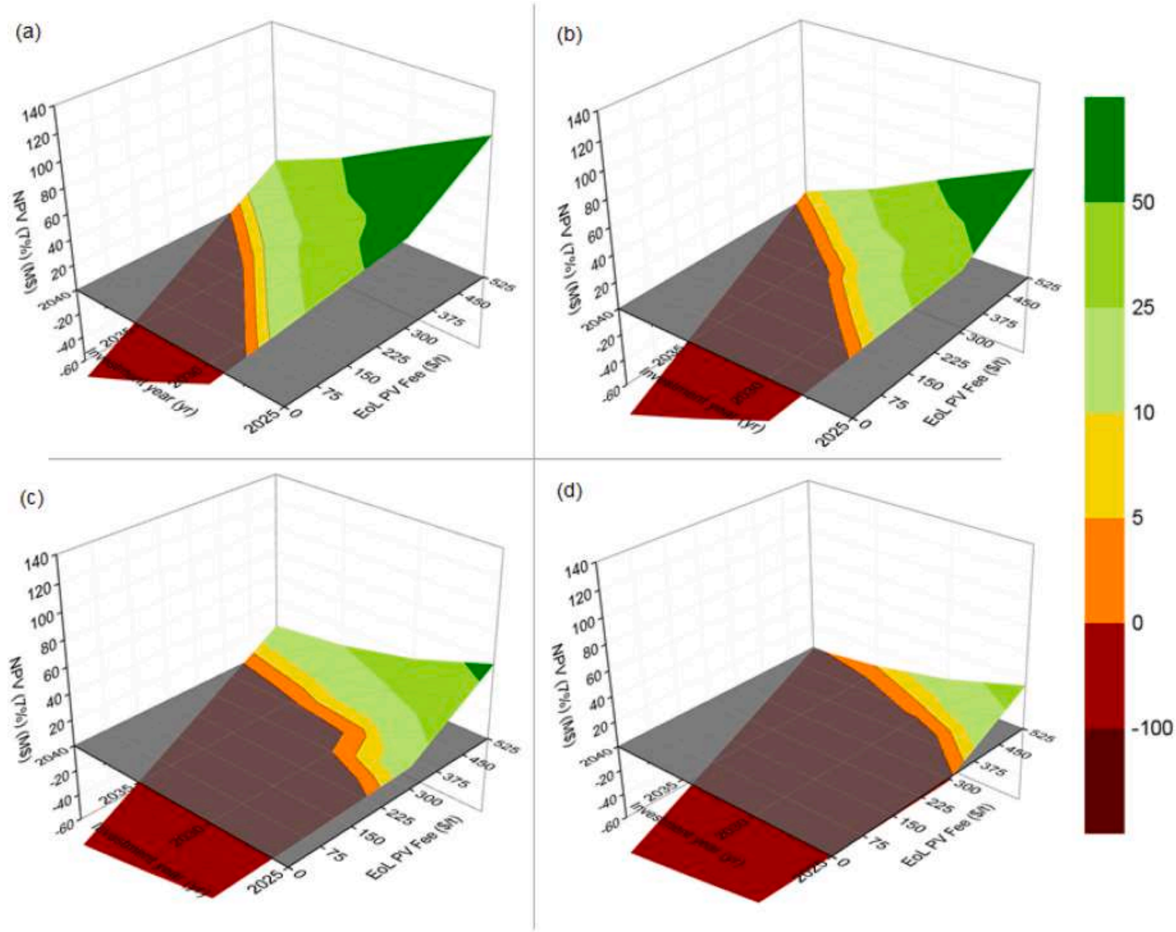

Fig. 11. NPV of different investments between 2025 and 2040 under the assumption of medium Ag concentration scenario: (a) PV 30,000 t/yr, regular loss (α = 5.4), (b) PV 27,000 t/yr, regular loss (α = 5.4), (c) PV 30,000 t/yr, early loss (α = 2.5), (d) PV 27,000 t/yr, early loss (α = 5.4). (Ag price: 750 $/kg).

materials (D'Adamo et al., 2017). In fact, switching to a high Ag concentration scenario (supplemetary information) generates high NPVs without PV fees in a wider PV throughput scenario. Agreements between different stakeholders on recycling fees would increase further the overall economic sustainability in PV recycling, as also pointed out in previous research (Daniela-Abigail et al., 2022).

5. Conclusions

The economic sustainability of PV recycling depends on recycling volumes and Ag revenues. As long as the Ag concentration remain in the range 0.1–0.2% it is possible to recycle EoL PV panels without adopting any PV fee to sustain the process. However, this will be hardly the case given the decreasing Ag concentration in PVs. In this case, the sustainability will depend on the actual Ag concentration in PV waste, which can vary from a low to high scenario, and of course on the Ag selling price. Although earlier investments will be in general more profitable, in the likely scenario of a medium Ag concentration the role of PV fees will be crucial to sustain recycling. In this case, PV recycling fees of about 20% of the unit processing cost will be enough, unless the Ag price will not decrease again below 750 $/kg. In this case as well, early investments (2025) on large recycling volumes (>30,000 t/yr) will be obliged conditions to achieve sustainability without PV fees.

Overall achieving sustainability in PV recycling requires (i) maximizing material recovery, (ii) having fewer larger recycling centers instead of many smaller ones, and (iii) prompting early investments. Besides, a wise distribution of economic resources between recyclers, recycling consortia, PV manufacturers, and public administration will be essential.

CRediT authorship contribution statement

Giuseppe Granata: Conceptualization, Methodology, Investigation, data collection, Writing – original draft. **Pietro Altimari:** Formal analysis, Writing – original draft. **Francesca Pagnanelli:** Conceptualization, Writing – original draft, Resources. **Johan De Greef:** Investigation, data/evidence collection, Writing – review & editing.

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.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jclepro.2022.132384.

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