Progress in recovery and recycling of kerf loss silicon waste in photovoltaic industry

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\textbf{A B S T R A C T}

With the rapid growth of the photovoltaic (PV) industry, the amount of the silicon waste has substantially increased, resulting in serious environmental problems. This waste mainly consists of the silicon waste powder from kerf loss slurry of wire saw wafer cutting process and the scrap pieces from silicon ingot casting process. To reduce the cost of crystalline Si production and relief the existing environmental pollutions, it is of significant interest to recover and recycle the silicon value from the Si waste. This paper presents a literature overview of the current technologies and research progress in the recovery and recycling of high purity silicon from the silicon wastes generated in the PV industry. First, the source and classification of Si wastes, including slicing silicon wafer and scraps of Si ingots are summarized. Second, various techniques related to the separation and recovery of high purity Si from the waste are reviewed and compared based on the experimental results. The characteristics and advantages of different technologies are evaluated based on the current conditions. Third, the applications of silicon waste are explored in a detailed manner. Last, the assessment of different Si recovery technologies is elaborated. This review gives an outlook on the recycling and recovery of high purity silicon from the silicon waste, which shows great potential for further research in this field.

1. Introduction

Recently, Si-based solar cells are experiencing a rapid development in the renewable energy field due to the advantages of cleanliness and low pollution. Over 94% of the solar cells are produced using crystalline silicon in the photovoltaic (PV) market \cite{1,2}. In the production of crystalline Si solar cells, approximately 60% of the total manufacturing cost stems from the expenses associated with the production of silicon wafers \cite{3,4}. Multi-wire sawing process of crystalline Si ingots is an effective strategy, from which Si wafers are produced \cite{5}. The total production of Si-based solar cells was about 100 GW in 2017, and about 400,000 tonnes of crystalline Si were consumed chiefly by Siemens process \cite{6,7}. This process \cite{8} is a mature route to purify metallurgical grade silicon into solar grade Si. The process starts from an acid attack of silicon by HCl at moderate temperatures (300–400 °C), yielding trichlorosilane (SiHCl\textsubscript{3} or TCS) and silicon tetrachloride (SiCl\textsubscript{4} or STC) as by-products. The mixture (TCS and STC) is distilled, and the TCS is then decomposed with the aid of hydrogen at a high temperature (1100 °C) to produce crystalline Si. Unfortunately, over 40% of the used Si is discharged as kerf loss waste during the multi-wire sawing process. This waste amounted to nearly 160,000 tonnes in 2017 \cite{9}.

The kerf loss Si waste mainly consists of high purity Si particles, abrasive SiC particles, cutting oil (e.g. polyethylene glycol (PEG)) and shredded metal fragments \cite{10}. Discharging these slurry wastes directly into the environment not only results in pollution but also accentuates the wafer manufacturing cost because of the disposal costs of the slurry waste. However, these materials have great value and can be reused and recycled, an aspect which has resulted in the field receiving...
increased attention in the recent years. Therefore, the effective recovery of high purity Si from the Si wastes is becoming an important issue for the sustainable development of PV industry. The development of appropriate recovery, recycle, and reuse technologies is crucial for this purpose [11]. The recycling of kerf loss Si, abrasives (SiC or diamond) and lubricating liquid (cutting oil) is necessary to reduce the waste, increase the value of the products and make the process economically feasible [12,13]. Another Si-bearing waste is the Si ingot pieces that is cut from the top and sides of the ingot, where inclusions (e.g. Si₃N₄) lining refractory materials, and graphite heating elements exists [14,15].

If the kerf loss Si waste and scraps of Si ingot pieces are recovered, recycled and reutilized, it will not only reduce the negative impacts on the environment, but also decrease the manufacturing cost of Si-based solar cells. Hence, to lower the energy consumption, curb the environmental pollution and save the manufacturing cost, the recovery and recycling of high purity Si particles from the kerf loss Si waste is essential. However, this process remains to be a challenge because of the huge disposal costs related to the Siemens method of Si purification at present.

To investigate the feasibility of Si recovery from the wastes, several researchers have proposed various separation and purification techniques in the past few years and have achieved great progress. Although some previously-published review papers have introduced the development in handling kerf loss slurry waste [13,16], the different technologies need to be compared comprehensively and the latest advancement was explored in detail. These references provide us some instructive guidance for this review work. Compared with the previously-published review papers, we make great attribution on this paper. At first, the characterizations of different silicon wastes are introduced and compared with each other, especially for the reasons on different impurities in the silicon waste in detail. Moreover, the composition of kerf loss slurry waste from different sources are compared, which can help the researchers to understand the characterization of the silicon waste. Secondly, we review almost all the recovery and recycling technologies on the silicon waste. According to the characterization, we make a classification as physical method, chemical method, metallurgical method, and other method. As for every method, we review and make an overview on different treatment ways in detail. Eg. we make a comparison on the removal fractions of metals with different acid solutions from different researchers, which is benefit for researchers to select optimal parameters. Thirdly, as for the application of kerf loss silicon waste, we systematically evaluate the application fields, such as electrocatalyst, photocatalyst, lithium ion batteries, porous/mullite ceramics and nano-silica materials. The performances of kerf loss silicon waste in different application are overviewed. At last, we make a technologies evaluation on silicon waste recycling, and propose an outlook, which provides some instructive suggestions for researchers in the further work. This literature review provides a fresh perspective on the recycling and recovery of high purity Si from Si wastes and demonstrates the great potential for further research in this field.

2. Source and classification of silicon wastes

Fig. 1 depicts the manufacturing chain in the PV industry, which is referred and modified from the literature [9]. The main Si wastes include the kerf loss Si waste from multi-wire sawing process and scraps of Si ingots from the casting process [14,17–19]. Based on the differences in the silicon sources, Si waste can be divided into two types: kerf loss Si waste and scraps of Si ingots. Fig. 2 shows the classification of Si wastes. Their detailed characteristics are illustrated in the following sections.

2.1. Saw slicing waste

Multi-wire sawing is widely used in the slicing of various hard-brittle materials, such as Si and quartz crystal. As a tool, the saw consists of a steel wire with a diameter of 0.2 mm or less, which is passed through grooves of guide rollers to several hundreds of iterations or more [20]. Fig. 3 gives a schematic diagram of a multi-wire sawing system for Si wafers [21]. In the process, only parts where the wire is routed are cut. It is possible to simultaneously slice several wafers corresponding to the number of iterations which makes the wire wound around the machine [22]. Si wafers are obtained by slicing a high-purity mono or polycrystalline Si ingot by using loose abrasive and fixed abrasive multi-wire saws. 2.1.1. Loose abrasive slurry sawing waste

The loose-abrasive sawing (LAS) method uses loose abrasive SiC particles suspended in a coolant carrier fluid (typically PEG-200) by the moving steel wire [23,24]. The wire can be straight or structured, with the latter allowing higher speed rates than the former. SiC displays superior corrosion resistance, mechanical properties, thermal stability and oxidation resistance [25]. Green SiC particles are traditionally applied to cut material of high hardness and brittleness, such as crystalline Si, super-hardness alloy and optical glass [26]. Therefore, the main abrasion process is the brittle fracture of Si caused by a three-body interaction process with the SiC particles and the steel wire. The silicon ingots are cut by the rolling motion of the abrasives between the steel wire and the ingots [27]. The cutting kerf loss slurry waste mainly contains high-purity Si particles, abrasive SiC particles, metal fragments and polyethylene glycol (PEG) solution.

The composition of the kerf loss Si slurry waste from different sources is listed in Table 1. The main constituents are SiC particles and PEG solution. The Si powder in the waste can be regarded as a potential source of solar grade silicon because of its intrinsically high purity. The major challenge in the recycling of kerf loss Si waste is the separation and recovery of the high-purity Si powder from the Si loss waste in a cost effective and robust manner. The major impurities in the kerf loss Si slurry waste are Fe, Al, Ni, K, Na, and P [28]. Fe and Ni impurities are chiefly from the coating agent and the steel wire of the fixed abrasive steel wire [29]. The source of Al is identified to be the Al mounting stage used during the crystalline Si ingots slicing process [30]. P, having a concentration of 7.49 × 10⁻⁶ in the kerf loss Si waste, may result from the contamination of phosphates from the coolant water [28]. The particle size distribution of the slurry Si waste given in Fig. 4 demonstrates the difference between Si and SiC. Si has an average particle size of 1.00 μm and is much smaller than SiC, which has an average particle size of 9.24 μm [31].

2.1.2. Diamond wire sawing waste

Compared with the aforementioned LAS process, diamond wire sawing (DWS) method is more competitive because of its huge potential and 2–3 times higher productivity [27]. A steel wire containing diamond abrasives is used for slicing method. During the DWS process, the crystalline Si ingots are cut by the diamond particles that are embedded in a nickel or resin coating on a steel core wire. The diamond grits are impregnated or electroplated onto the stainless-steel wire as fixed cutting points [5], resulting in high activity and complex chemical reaction for releasing the impurities [6]. Water-based coolant is introduced instead of the organic abrasive slurry [37], which is more environmentally friendly. However, the diamond wire sawing kerf loss slurry is a complex waste, which contains a large amount of metallic inclusions and organic solvent (cutting oil) from the polymeric lubricant. The Si loss caused by the DWS process amounts to approximately 34% of the Si ingot weight [37].

The diamond sawing silicon wastes are in the form of debris or flakes or flakes, as shown in Fig. 5(a). The size distribution of the Si particles from DWS is centered around 2 μm as shown in Fig. 5(b), which is similar to that of the Si particles from the LAS process. The diamond sawing wire diameter was reduced slightly to 75 μm from 75.5 μm (top photograph), as shown in Fig. 5(c) due to the loss of the
2.1.3. Comparison of the two sawing wastes

Table 2 compares the LAS and DWS processes. DWS is a more sustainable manufacturing process than LAS. First, DWS uses diamond abrasives with a hardness of 60–120 GPa, which is 3–4 times higher than that of the SiC abrasives. The latter exhibits greater abrasion resistance. Second, the coolant used in DWS is a water-based solution with a lower operating temperature, and generates less hazardous wastes [38]. Third, smaller diamond abrasives (8–10 μm) can generate a smaller variation of the total thickness variation during the sawing process [39]. Compared with the LAS slicing process, the cutting time for 156 mm square wafers was shortened from 6.8 h to 2.8 h, and the production capacity of Si wafers increased from 6500 wafers per day to 13,800 wafers per day for a diamond slicing machine, which translates into higher yields. During the LAS process, the removal rates of the Si ingots are restrained by the rolling and indenting action of the loose abraded diamond particles and the nickel coating layer on the wire [9].

### Table 2

<table>
<thead>
<tr>
<th>Ref.</th>
<th>Si (%)</th>
<th>SiC (%)</th>
<th>PEG (%)</th>
<th>Metal Fe (%)</th>
<th>SiO₂ (%)</th>
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</thead>
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<tr>
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<td>6.1</td>
<td>46.56</td>
<td>46.56</td>
<td>0.79</td>
<td>/</td>
</tr>
<tr>
<td>32</td>
<td>53</td>
<td>17</td>
<td>/</td>
<td>1</td>
<td>29</td>
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<tr>
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<td>16.4</td>
<td>26.2</td>
<td>12.9</td>
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</tr>
</tbody>
</table>

abraded diamond particles and the nickel coating layer on the wire [9].
grits, and the movement speed is less than that of the stainless steel wire speed, resulting in a lower productivity of the Si wafers. On the contrary, DWS process applies ductile mode cutting method to obtain wafers of superior quality, with high removal rates and without sacrificing the productivity. According to the International Technology Roadmap for Photovoltaics (ITRPV) [6], the DWS technology performs well on mono-crystalline and polycrystalline Si ingot wafers, and is of late becoming the preferred wafer slicing technology. This trend is supported by the fast introduction of wet chemical texturing methods for the DWS Si wafers.

2.2. Scraps of polycrystalline silicon ingot

Polycrystalline Si ingots are prepared in silicon nitride (Si₃N₄)-coated quartz crucibles. Silicon nitride, an anti-sticking layer, is utilized to prevent the adhesion of crystalline Si ingot onto the crucible walls [30]. During the solidification process of crystalline Si, certain inclusions, such as Si₃N₄, lining refractory materials and carbon from the graphite heater, will be penetrated or segregated towards to the top and sides of the Si ingot [15]. As a result, the contaminated parts should be cut off before the Si ingots are sliced to wafers [43]. From the literature [14], it could be discerned that the top of the crystalline Si ingot, with a thickness of 110–120 mm and weight percent of 10% of the whole Si ingot, is contaminated by the inclusions such as SiC, Si₃N₄, Fe, and Al. The main inclusions in the scraps are needle-like Si₃N₄ and bulk SiC particles [14]. These inclusions do not dissolve and would be incorporated in the polycrystalline Si ingot during the Si melting process. The morphologies of the crushed top-cut Si scraps of the ingots are portrayed in Fig. 6. SiC and Si₃N₄ needles easily agglomerate as clusters. The length of the Si₃N₄ particles is over 500 μm and the average diameter is 20 μm; however, the length of the SiC particles is much smaller than 500 μm. Moreover, the side of the ingots, with a thickness of 5–20 μm, is cut off to make them square in shape. If the inclusions such as SiC and Si₃N₄ can be eliminated from the scraps to an acceptable level, the recovered Si will become a valuable material for the recycling application of Si waste in the PV industry.

3. Overview of different technologies for Si recovery

The Si waste contains Si ingot scraps, high purity Si powder, large SiC abrasive particles and other coolants (eg. PEG), which have attracted attention for the separation, recovery and recycling of Si waste in the recent years. Several technologies related to the separation and recovery of high purity Si have been overviewed. Typically, the following sections provide a summary of the latest research progress in the field and describe four types of technologies based on the characteristics of the processes. The merit of the physical method, chemical method and metallurgical method are discussed. The categories of Si recovery methods are presented in Fig. 7.

3.1. Physical method

3.1.1. Phase transfer separation method

Phase transfer separation method is used to obtain a high concentration of Si from the kerf loss waste. The process consists of the following four steps:

- PEG solution removal by solvent solution (such as acetone)
- Metal fragment removal by acid leaching (HCl, HNO₃, H₂SO₄, HF, etc.)
- Si (2.33 × 10³ kg/m³) and SiC (3.22 × 10³ kg/m³) separation by an intermedia solvent (such as water or sodium polytungstate with a density of 2.8 × 10³ kg/m³)
- Filtered and dried Si-rich and SiC-rich powders

Table 2

<table>
<thead>
<tr>
<th>Abrasive particles</th>
<th>SiC</th>
<th>Diamond</th>
</tr>
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<tbody>
<tr>
<td>Hardness (GPa) [40,41]</td>
<td>19.3–29.7</td>
<td>60–120</td>
</tr>
<tr>
<td>Slicing [24]</td>
<td>PEG</td>
<td>Water based solution</td>
</tr>
<tr>
<td>Feed rate [42]</td>
<td>0.42 mm/min</td>
<td>1.1 mm/min</td>
</tr>
<tr>
<td>Cutting time 156 mm × 156 mm [42]</td>
<td>6.8 h</td>
<td>2.8 h</td>
</tr>
<tr>
<td>Wafer production capacity (156 mm × 156 mm) [42]</td>
<td>6500 wafers/day</td>
<td>13,800 wafers/day</td>
</tr>
<tr>
<td>Temperature rise [39]</td>
<td>40–60 °C</td>
<td>&lt; 20 °C</td>
</tr>
<tr>
<td>Environment &amp; economics [11]</td>
<td>PEG slurry increasing hazardous waste; Larger kerf Si loss; Yield larger depth of damage; Comparatively lower productivity; Higher cost of waste treatment</td>
<td>Water-based fluid to reduce the hazardous waste; reduce kerf loss; yields smaller depth of damage; higher productivity; Lower cost of waste treatment</td>
</tr>
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</table>

Fig. 5. (a) SEM image of the diamond sawing Si kerf; (b) size distribution of the Si waste particles; (c) SEM images of the diamond sawing wire before and after wafer slicing [9].

Table 2

Comparison of slurry sawing Si waste and diamond wire sawing Si waste.

<table>
<thead>
<tr>
<th>Loose abrasive slurry sawing (LAS)</th>
<th>Diamond wire sawing (DWS)</th>
</tr>
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<tbody>
<tr>
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</table>
Single layer solvent and double layer solvent are two common types of solvents used in the phase transfer separation process, which takes advantage of the distinct specific gravities of the components, as shown in Fig. 8. Li et al. [44] investigated the separation of Si and SiC using water as the solvent, which is the single layer solvent system. In the raw slurry waste, the average size of the SiC particles was 6.6 μm, which was 3.7 times larger than that of the Si particles (1.8 μm). According to Stock’s law, the settling velocity ratio of SiC/Si was 19.6, favoring the separation of Si and SiC particles during the gravity sedimentation process in water. Under the condition of solid/liquid ratio of 0.08 and sedimentation time of 5 h, the SiC particles settled down to the bottom of the water, and the Si particles floated to the top, as represented in Fig. 8(a). The highest recovery of the Si particles reached 79% in the Si-rich powder. Moreover, 12.8% SiC, 6.84% Fe, $21 \times 10^{-6}$ B and $16 \times 10^{-6}$ P remained in the Si-rich powder. Sodium polytungstate was also applied as the intermedia solvent ($2.8 \times 10^3 \text{ kg/m}^3$) to separate the two particles, and the largest recovery of Si was about 85% with the use of single gravity sedimentation process [44]. This result indicates that sodium polytungstate is more effective than water when used in the phase transfer separation process.

Lin et al. [36] tested a two-step phase-transfer process to separate and recover Si particles from the slurry waste. The kerf loss Si slurry waste was pretreated with acetone and HNO$_3$ (30 wt%) solutions to remove the PEG and metallic inclusions, respectively.

In the first stage, the pretreated Si waste was mixed with the oil phase, and the dispersant used was sodium hexametaphosphate (Na-HMP) having a density of $1.1 \times 10^3 \text{ kg/m}^3$. The influence of various factors such as pH of the solution, oil/water ratio and liquid/solid ratio...
on the separation and purification of Si was investigated. After phase transfer treatment, the larger SiC particles of around 9 \( \mu \)m were extracted into the oil phase, and then sunk to the bottom of the tube due to its hydrophobicity and gravitational force. As a result, the Si-rich particles were suspended in the aqueous phase, and were collected with a purity and recovery of 96.6% and 80.3%, respectively. However, the sub-micron SiC particles remained mixed with the Si powder and were left behind in the water.

In the second stage, the density of the oil phase was adjusted to 0.82 \( \times 10^3 \) kg/m\(^3\), which is lower than that of water. The sub-micron SiC particles were further extracted from the Si-containing water to the light oil phase, which promote the Si separation. On the other hand, the Si product remained in the aqueous phase. The results showed that after the two-step process, the maximum Si recovery and purity were 71.1% and 99.1%, respectively.

Wang et al. [45] selected methyl isobutyl carbinol (MIBC) and water as the two phases with the addition of sodium dodecyl sulfate (SDS) to separate Si and SiC powders from water phase to MIBC phase. The feasibility of SDS addition on the separation of Si and SiC was investigated. The transferred fraction of SiC increased to > 90% below pH 5 when 0.5 kg/ton SDS dosage, whereas that of Si increased to > 25% below pH 5 at the same SDS dosage. When 2 kg/ton SDS was added, the purity and recovery of SiC recovered in the MIBC phase were 80.7% and 98.3%, respectively, and those of Si recovered in the water phase were 97.0% and 70.1%, respectively. These results demonstrated that SDS addition can improve the separation ratio of SiC and Si in the kerf loss slurry waste at an optimal pH 5. The mechanism of phase transfer separation with SDS surfactant collector addition was explained. When a surfactant collector (SDS) is added and selectively reacts with SiC powders, the SiC powders become more hydrophobic and will be mostly wetted by oil droplets. On the contrary, Si powders that do not react with SDS will retain in the water phase; thus, the two powders are separated. Therefore, high purity and recovery of SiC and Si can be obtained in each phase through a one-step phase transfer separation operation.

Wei et al. [46] selected kerosene as the oil phase to separate Si from the Si slurry waste. The separation efficiency depended on the kerosene content in the slurry. The optimal amount of oil was in the range of 1.7–2.0 wt%. The Si grade of the Si-rich powder was 99.3 wt%, and the yield reached 93%. Fig. 9 shows the stratification of the oil and water in the phase transfer process. Most SiC particles moved to the upper oil phase, while the Si particles were enriched in the lower aqueous phase.

Double-layer solvent sedimentation process is another novel method to separate Si and SiC particles from the Si waste, and the method was proposed by Xing et al. [33]. The schematic illustration is given in Fig. 8(b). Two organic solvents with different densities were selected for mixing with the Si-SiC slurry to separate the Si and SiC particles. By calculating the SiC/Si velocity ratio, the optimum solvents were inferred to be carbon tetrachloride and chloroepoxy propane for the separation process. Because of the relatively higher density and lower
polarity, carbon tetrachloride was chosen as the bottom solvent. On the contrary, chloroepoxy propane was selected as the upper solvent because of its relatively lower density and higher polarity. After 10–15 min, most of the SiC particles moved to the solvent 2 (downside) and were collected from valve 2. The purity of the SiC-rich powder was 94.73 wt%, which still contained 3.89 wt% Si, and 0.26 wt% Fe. Most of the silicon particles remained in the solvent 1 (upside) and collected from valve 1. The purity of the Si-rich powders was 95.04 wt%, which contained 3.81 wt% SiC and 0.22 wt% Fe. Subsequently, the separated Si powder was pressed into pellets, and melted above 1500 °C in Ar atmosphere to obtain Si ingot with a purity of 99.06%.

Table 3 outlines Si and SiC separation using different intermedia solvents. The recovery of Si can reach a maximum of 95% after gravity sedimentation method. From the perspective of scale application, it has the advantage of cost effectiveness and ease of operation. When compared with the single layer sedimentation process, the separation efficiency of the double-layer sedimentation method is higher. Although gravitational settling method works well for the separation of the large Si and SiC particles, the separation of the ultra-fine particles (either Si or SiC) remains a challenge, which lowers the overall yield and purity of the Si-rich powders.

3.1.2. Centrifugal separation method

Centrifugal separation is another effective strategy to separate Si and SiC from the Si waste, which takes the advantage of the density difference in both. During the centrifugation process, the solvent medium can be either water or organic solvents such as bromoform and ethanol [35,47].

Liu et al. [47] studied the centrifugal separation of Si from the slurry waste via modifying the surface potential of the particles. In their research, the medium of the solution was water, and the surface charge level of the pre-dispersed Si and SiC mixture was adjusted by the addition of hydrochloric acid or sodium hydroxide solution. The recovery flow chart is illustrated in Fig. 10. After the centrifugation, the upper suspension consisting of Si-rich powder was separated. The sink powder solution was adjusted to pH 8.15 and again centrifuged. After three rounds of centrifugation, the Si-rich powder was recovered in the upper part with a grade of 91.8% and the SiC-rich powder was present in the bottom part with a grade of 95.2%. Varying the pH value of the solution had a significant effect on the surface charges of the Si and SiC particles. When the pH was 4, the zeta potentials of Si and SiC powder were about 20 mV. The repulsion between Si and SiC particles was relatively weaker, which made the larger SiC particles sink faster. However, when the pH was increased to 8, the surface charges of the Si and SiC particles increased, which enhanced the repulsion between Si and SiC particles and prevented the ultra-fine Si powder from settling down to the bottom of the tube under the centrifugal force. Correspondingly, the larger SiC particles moved towards the bottom more easily with the centrifugal force.

Lin et al. [35] selected the mixture of 96 wt% bromoform (CHBr₃) and 99.5 vol% ethanol as the heavy liquid to separate the Si and SiC powders by centrifugation. After the process, the upper layer cake comprised Si-rich sample, and the sediment layer was SiC-rich sample. The density of the solution was adjusted by varying the ratio of bromoform and ethanol. When the density was increased from 2.35 to 2.86 g/cm³, the purity of the Si powder decreased from 93.7% to 68.2% under a gravity coefficient of 2180 g and duration of 60 min. Correspondingly, the yield of Si powder increased from 46.1% to 70.3%. In the solvent with a large density, the fine SiC particles are easily trapped and agglomerated with the Si particles, floating to the top of the solution. On the contrary, when the density of the solvent is small, the fine SiC particles settle down to the bottom rapidly due to the gravity, mitigating the agglomeration with the Si particles. Hence, the purity of the separated Si increased with the drop in solvent densities. Moreover, a hydrophilic silica-coated layer was formed on the surface of the particles in the CHBr₃ solution due to the acid pretreatment, thereby promoting the agglomeration of the particles with each other [48]. Thus, it is nearly impossible to thoroughly separate the ultra-fine SiC powder from the Si waste by centrifugal or gravitational processes because of the small density between the two. Although centrifugation is effective for the separation of large SiC particles, it is not effective for the removal of the submicron-sized SiC particles [36,49]. Therefore, the purity of the Si powder needs to be further enhanced.

3.1.3. Hydrocyclone method

Hydrocyclone is an apparatus used to separate and sort different particles present in a liquid phase based on the ratio of centrifugal force and fluid resistance [50]. Sergienko et al. [51] applied hydrocyclone to recover SiC particles from kerf loss Si waste. At first, a filter/press process was used to eliminate PEG. Secondly, the Fe particles were eliminated by a high gradient magnetic separation process. Thirdly, the hydrocyclone process was utilized to separate SiC and Si particles. A schematic diagram of a pilot plant was illustrated in Fig. 11. Ten percent powder mixed with water was injected into the slurry tank 3 (Fig. 11). The capacity of the hydrocyclone was about 400 m³/h, and the slurry tank contained 100 hydrocyclones. In the first stage, the relatively larger Si and SiC particles settled down in the tank 5 after 30 min of hydrocyclone treatment. Then, SiC particles went to the sedimentation tank 6, and the composition of the received sample was 85% SiC, 13% Si and 2% Fe in the tank 6. To recover the residual Si particles in the SiC matrix, the SiC-rich sample produced after the first treatment was reloaded into the tank 3 and underwent an additional treatment. It was found that after second treatment, the concentration of Si in the SiC-rich sample was reduced to 4% with SiC of 95% and Fe of 1%, which was acceptable composition for recycling to the cutting process as abrasive particles. Moreover, the purity of the recovered Si powder achieved the maximum value of 94%. Furthermore, a much higher purity (98%) and recovery (88%) of the recovered SiC powder by the hydrocyclone separation were reported by Lee et al. [34].

3.1.4. Magnetic separation method

Magnetic separation is based on the fact that the particles in the
wastes differ in the degree to which they are attracted by a magnetic field. Due to the simple operation and low pollution, it is regarded as an economical strategy to separate the magnetic elements from the wastes [52]. Tsai et al. [53] used the magnetic separator to remove iron from the Si waste. During the process, the particles experience four main forces, namely gravitational force (Fg), magnetic force (FM), drag force (FD) and buoyant force (FB), as shown in Fig. 12(a). Iron is a ferromagnetic material; hence, the Fe-containing inclusions can be magnetized and attracted to the magnetic collector. Based on literature [54], the iron scraps in the kerf loss Si waste could be divided into two types. One type is in the form of individual Fe element, which can be attracted directly by the magnet. The other type is in the form of ultra-fine Fe particles which adheres to Si or SiC particles. Since Si and SiC particles contained limit ultra-fine Fe particles and were not susceptible to the magnetism, they were separated from other inclusions/impurities with enough amount of Fe. From the literature [53], it was understood that when the magnetic field was increased to 0.44 T from 0.1 T, the Fe removal fraction reached 48%. Since Zn and Cu are non-ferromagnetic substances, their removal fractions of Zn and Cu showed no obvious hike with the increase in magnetic intensity. After five cycles of magnetic treatment, the removal fraction of iron increased to 98% at 0.44 T with a viscosity of 19 mPa·s. Liu et al. [54] found that ammonia had a favorable influence on the removal of the magnetic materials in the wastes, and the magnetic substance content decreased from 79.02% to 23.05% with the addition of 10% ammonia. Noted that the microwave-assisted technology has been applied to deagglomerate the Si-rich particles via modifying the surface potential of the particles. According to the DLVO theory [55], the electrostatic repulsion experienced by the Si powder was relatively larger at pH 13.0, which kept the ultra-fine Si-rich powder sufficiently dispersed. Boutouchent-Guerfi et al. [5] stated that wet magnetic separation is more effective than dry magnetic separation in metal removal.

High gradient magnetic separation (HGMS) technology was applied to separate high purity Si from kerf loss Si waste by Yang et al. [56]. The superconducting HGMS has the advantage of enhanced magnetic flux density (maximum 5.5 T), energy-efficiency, cost-effectiveness and absence of secondary pollution [52,57]. Also, the process is highly suitable to capture the fine weakly magnetic particles [58]. Under the optimum parameters of Si slurry density 20 g/L, magnetic flux density 4.0 T, and Si slurry flow velocity 500 mL/min, the purity of Si increased to 95.83% from 90.91%, and iron content was reduced from 3.24% to 0.57%. Sergienko et al. [51] also selected HGMS to remove iron particles. They found that when the tape speed was 0.2 m/s, Fe in the wastes was removed lowered to 50–55% after the magnetic separation process. The HGMS works well for the ferromagnetic matter such as iron, however, non-magnetic particles such as SiC, Cu and Zn needs to be removed by other methods.

3.1.5. Electrical field method

Based on the differences in physical properties such as particles size distribution, density, and surface charge between the SiC and Si particles in the kerf loss Si waste, an electrochemical apparatus was designed...
to separate Si and SiC particles. The technique made use of an electrical field method combined with gravity sedimentation [17,31,59]. In the pre-treatment step, the Si waste particles were mixed with the buffer solution, and the pH values were adjusted using H₃PO₄ and NH₃ [17]. Two different kinds of sedimentation tanks were used to separate the Si and SiC powders under gravitational and electrical fields. Wu et al. [60] utilized a rectangular tank to collect the sedimented particles, and the operation lasted for 24 h at 1 V/cm within a horizontal electrical field, as shown in Fig. 13(a). When the pH value of the buffer solution was greater than 2.5, the negative charge on the Si specific surface was higher than that on the SiC particles, which caused the Si particles to move faster towards the anode. Because of the smaller particle size and density of the Si particles in the slurry, they were concentrated at the bottom of the cell under the electrical field. Only 7.15% of the SiC particles remained near the electrochemical cell outlet. Besides, the electrical field was modified by Tsai et al. [31]. The rectangular tank was changed into a ramp tank, which can shorten the distance travelled by the small particles for their collection and hence the sedimentation time. When the parameter of the electrical field was 1.0 V/cm at pH 7, the mobilities of the Si and SiC particles were $3.99 \times 10^{-8}$ and $3.34 \times 10^{-8}$ m²/V·sec, respectively. The SiC particles settled near the inlet rapidly as their size and density were larger than those of the Si particles. The Si powder had more negative charges than the SiC powder, which made the Si particles move towards the anode. Therefore, the content of Si at position 8 was higher than that at positions 2–5, as shown in Fig. 13(b). In the ramp tank, the highest grades of the recovered SiC and Si particles were 95.2 wt% and 7.01 wt%, respectively. When compared with treatment in the rectangular tank, the sedimentation time for Si particles (~1 μm) was shortened from 24 h to 6.58 h, demonstrating that the ramp tank had the potential to achieve a high yield rate.

3.1.6. Supercritical method

The supercritical method (e.g., application of supercritical water) was conducted to eliminate the cutting oil in the kerf loss Si waste [61]. This method is based on the differences in the dissolving abilities of various substances, such as organics and inorganics. Most of the organic substances, such as cutting oil, are completely miscible in supercritical water, whereas inorganic substances, such as Si and SiC, are almost insoluble. Hence, the use of a supercritical process is regarded as an effective way to separate organic materials from the Si slurry waste. The dielectric constant is a critical parameter to determine the dissolving ability of a medium [62]. The schematic diagram of the supercritical water elutriation of kerf loss Si slurry waste is illustrated in Fig. 14. The initial composition of the Si slurry waste was 25% cutting oil, 10% water and 65% Si powder, as determined by thermogravimetric differential thermal analysis. From the literature [62], the main components of the cutting oil were inferred to be straight-chain alkanes whose...
The faces of the Si and SiC particles display the properties of hydrophobicity activated by the HF solution. The surface was modiﬁed by the HF attack generated a H-terminated surfaces. Because HF-etched and H-terminated Si surface mechanism. The surface oxide was removed in the HF solution. Based on the experimental results, it was understood that the F ion does not terminate the Si dangling bonds on the surface but rather inhabits the interstitial site just below the Si surface [67].

Li et al. [68] applied surfactant poly (propylene glycol) bis (2-amino propyl ether) (PEA), a collector, to facilitate the separation of Si and SiC from kerf-loss Si waste during flotation process. The effects of PEA on the single Si/SiC and Si-SiC mixture powders were compared. The mechanism of Si waste flotation on PEA was analyzed by zeta potential measurement, FT-IR spectra, and XPS. The maximum recoveries rate of SiC and Si were 90.59% (pH 9.00) and 80.93% (pH 1.96), respectively. Furthermore, the maximum Si grade was determined as 92.31% at pH 8.95 for the sinking part of the mixture generating excellent floatability and selectivity.

Moreover, investigate the adsorption mechanisms of different agents in Si and SiC during the flotation process, a single SiC flotation experiment on particle separation and recovery was conducted by some researchers [69,70]. Shibata Junji et al. [69] selected the cationic surfactants of dodecyl-tri-methyl-ammonium chloride (DTMAC) and trimethyl-octyl-ammonium chloride (TMOAC) to recover SiC particles by flotation process. When the SiC content was 0.3 wt% and surfactant concentration was $9 \times 10^{-4} \text{ mol/dm}^3$ in the cell, the highest recovery of SiC with DTMAC was 78% at pH 6.0. However, the recovery of SiC with TMOAC was 38% at pH 9.0. This difference was attributed to the fact that DTMAC conﬁrmed stronger hydrophobicity to the SiC surface than TMOAC because the former has a longer alkyl carbon chain as the hydrophobic group than the latter. The zeta potential result demonstrates that while the SiC particles are positively charged in the lower pH range (less than 2.3), they are negatively charged in the higher pH range. When the pH is over 2.3, the occurrence of a strong electrostatic attractive force between the SiC surface and the cationic surfactant species accentuates the adsorption of the surfactants. Iskra [70] investigated the flotation mechanism of SiC with anionic and cationic collectors. From the findings, it was concluded that the adsorption of the anionic collector (sodium oleate) was influenced by the intermolecular forces between the hydrocarbon chain of the collector and the atom carbon in the SiC lattice. The ﬂotation of SiC by means of cationic collectors (dodecylenammonium chloride) is easier than that by anionic collectors (sodium oleate). The mechanism of amine action in the flotation of SiC involves the adsorption of amine as a result of its electrostatic interaction with the negatively charged SiC surface. Besides, an inactive carbon is present in the crystallographic lattice of SiC. On the surface, some unreacted colloidal carbons may be found in the form of inclusions.

**3.1.7. Froth flotation method**

Froth flotation method works efﬁciently for the separation of ultratine powders in the wastes by selecting a speciﬁc collecting agent and modiﬁer to adsorb the target particles [63]. Flotation process involves only the surface property as a driving force for the separation. Huang et al. [64] used fatty acids as a selective collector of the SiC particles by froth ﬂotation method. With the increase in fatty acid content, the separation effect became stronger. When the concentration of the fatty acids was 0.315 mol/l, the highest recoveries of Si (95.9%) and SiC (99.3%) in the deposit and upper phase, respectively, were achieved at pH 4.5 and 70 °C. Fatty acid, as an anionic collector, is weakly acidic. As the pH surges, its dissociation in acidic conditions increases, thereby enhancing the removal fraction of iron and the ﬂotation separation efﬁciency. However, the surface of the SiC particles is negatively charged due to the adsorption of anions in water. When the SiC particles are gathered by an ion collector, the increase in pH value will rise electronegativity. This condition is not conducive for the collector on the surface of the SiC particles and will therefore the ﬂotation separation effect.

Li et al. [65] applied a two-step ﬂotation process to separate the Si and SiC from the Si slurry waste. HF was selected as the interface acti-vator to modify the surface characteristics of the particles. The surfaces of the Si and SiC particles display the properties of hydrophobicity and hydrophilicity, respectively [46]. When hydrofluoric acid was added to the kerf loss Si slurry waste, the silica layer on the surface of the Si particles and the Si—H bond on the particle surface were generated by the HF solution. The surface was modiﬁed to change hydrophilicity of the Si particles to hydrophobicity so that, the slurry can be separated by flotation. During the process, the appropriate concentration (0.8 mol/L and 0.6 mol/L) and potentials (−400 mV and −300 mV) were settled, respectively. After ﬂotation, the recovery of SiC was 52.8%, and its purity was 98.1%. Trucks et al. [66] explained the H-termination of Si surface mechanism. The surface oxide was removed by the HF solution, resulting in F-termination. Subsequently, the HF attack generated a H-terminated surfaces. Because HF-etched and H-terminated Si surfaces are hydrophobic, and the hydrophobic Si particle surface is produced in the HF solution. Based on the experimental results, it was understood that the F ion does not terminate the Si dangling bonds on the surface but rather inhabits the interstitial site just below the Si surface.

**3.1.8. Filtration method**

Filtration method is intensively applied in the removal of harmful inclusions in liquid Al and steel by using foam ﬁlters [71]. Zhang et al. [14,72] utilized ceramic foam filter to remove SiC and Si$_3$N$_4$ inclusions from the Si scrap by high temperature filtration method. A high va-cuum furnace was employed for the ﬁltration experiments. The schematic diagram of equipment is illustrated in Fig. 21. In the experiment, the Si scrap was melted at 1450 °C and then was subjected to the foam filter. Two types (carbon and SiC) of filters were used. The samples were heated to and held at 1450 °C. After ﬁltration, the liquid Si melt was passed through the filters, and no Si$_3$N$_4$ inclusions were detected in the melt. The main inclusions were small SiC inclusions with the size of 10 μm. The ﬁltration procedure includes four steps:

1. Removal of large Si$_3$N$_4$ rods and large SiC particles by cake ﬁltra-tion;
2. Removal of small Si$_3$N$_4$ particles and most of the SiC inclusions by deep-bed ﬁltration;
3. Formation of large SiC clusters and bridges across pores;
4. Formation of SiC layers by Si dissolution in the carbon filters.

Besides, more parameters involving in this ﬁltration separation are desired: the ﬁlter structure, inclusion category, and melt viscosity.
3.2. Chemical method

3.2.1. Acid leaching method

It is acknowledged that acid leaching method is one of the most effective ways to remove most of the metallic impurities such as Fe, Al, Ni, Ca, and Mg in the PV industry [73–75]. Particle size is crucial for the leaching process: the smaller the particle size of the Si waste powder, the higher the removal efficiency of the impurity. During the past few years, several kinds of acid leaching processes have been proposed to remove the metallic impurities from the kerf loss Si waste, including HCl solution leaching [76], H₂SO₄ solution leaching [77,78], HCl + HF mixture solution leaching [54], multivariate acid system leaching [9], and microwave mixed acid leaching [54]. The impurity removal within different acid solutions are compared in Table 4. The main metallic impurities are Fe, Al, Ca, Mg and Ni. The priority of acid on the impurity removal is HF > HCl > H₂SO₄. Although most of the metallic impurities are removed, there is still amount of impurities remains after leaching in the kerf loss Si waste. However, because SiC has the characteristic of being chemically inert, it is difficult to be removed by acid leaching treatment. Moreover, the SiC and Si particles have similar densities and their size distribution overlaps, which makes it difficult to achieve complete separation. Therefore, the acid leaching is only

| Table 4 |

| Removal fraction of metals with different acid solutions. |

<table>
<thead>
<tr>
<th>Agent</th>
<th>Parameters</th>
<th>Removal fraction</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>HCl 4 M</td>
<td>Microwave (800 W and 1200 W) leaching duration 3 h at 423 K</td>
<td>Al: 62%; Ca: 92%</td>
<td>[76]</td>
</tr>
<tr>
<td>HCl 4 M</td>
<td>Ultrasonic (150 W), at 423 K</td>
<td>Mg: 93%; Ni: 68%</td>
<td>[76]</td>
</tr>
<tr>
<td>H₂SO₄ 4 M</td>
<td>Microwave 800 W at 423 K</td>
<td>Al: 76%; Ca: 88%; Mg: 92%; Ni: 65%; Fe: 42%</td>
<td>[76]</td>
</tr>
<tr>
<td>H₂SO₄ 4 M</td>
<td>Ultrasonic (150 W) leaching duration 3 h at 423 K</td>
<td>Al: 62%; Ca: 80%; Mg: 88%; Ni: 68%; Fe: 18%</td>
<td>[76]</td>
</tr>
<tr>
<td>HCl 4 mol/L</td>
<td>60 °C, 3 h, liquid-solid ratio of 10</td>
<td>Al: 95.6%</td>
<td>[79]</td>
</tr>
<tr>
<td>HF/ HCl /H₂SO₄ 1 M or around 5 wt%</td>
<td>70 °C, 3 h with ultrasound treatment</td>
<td>Ni: 93.26%; Al: 95.83%</td>
<td>HF &gt; HCl &gt; H₂SO₄ [9]</td>
</tr>
<tr>
<td>H₂SO₄ 25 wt%</td>
<td>60 °C, liquid/solid ratio 10 mL/g, 200 rpm</td>
<td>Fe: 99.55%; Al: 95.53%; Ca: 95.33%</td>
<td>Multi times: B: 0.063 ppmw; P: 0.19 ppmw; Al: 1.1 ppmw; Fe: 0.31 ppmw;</td>
</tr>
<tr>
<td>H₂SO₄ 12%</td>
<td>Room temperature, 12 h, solid-liquid ratio 1:10</td>
<td>Fe: 85%; Al: 95%; Ca: 53%; Ni: 50%; B: 8%; P: 50%; Total: 90%</td>
<td>Activation energy: 10.78 kJ/mol and 35.97 kJ/mol not effective on B or P</td>
</tr>
<tr>
<td>H₂SO₄ 25 wt%</td>
<td>60 °C, 80 min liquid/solid ratio 10 mL/g, 200 rpm</td>
<td>Al: 95.74%; Fe: 93.16%; Ca: 93.28%; Ni: 88.89%; B: 69.44%; P: 10%w</td>
<td>B: 1.32 ppmw; P: 0.18 ppmw</td>
</tr>
<tr>
<td>HCl 15 wt%</td>
<td>70 °C, 240 min, 150 rpm</td>
<td>Fe: 94.96%; Ca: 99.08%; Al: 93.16%; Ti: 91.8%; Mg: 94.25%; Zn: 91.5%</td>
<td>[73]</td>
</tr>
<tr>
<td>HF-HCl mixture</td>
<td>Dissolving time 3 h, with Pre-dispersion and magnetic separation 3 h, 70 °C, liquid/solid = 4:1, stirring velocity 150 r/min</td>
<td>Fe: 91.35%</td>
<td>B: 143 ppmw → No detection P:239 ppmw → No detection</td>
</tr>
<tr>
<td>HCl (15 wt%)</td>
<td></td>
<td>Fe: 95.85%</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 15. Medium-scale acid leaching procedure [9].
selected as a pre-treatment for the separation and purification of Si from the kerf loss Si waste powder.

Kong et al. [77] applied diluted sulfuric acid with a concentration of 12 wt% to remove Fe from Si waste. Under optimum parameters of 60 °C, liquid/solid ratio of 10 mL/g and 200 rpm, the removal fraction of Fe reached 94.34%. The results of acid leaching kinetics demonstrated that the process followed the second order rate of homogeneous reaction model, and the apparent activation energies of the reactions in the two stages were 10.78 kJ/mol and 35.97 kJ/mol, respectively.

Yang et al. [9] proposed a composite technology combining acid leaching, calcination and deoxidation to remove the metal impurities in the kerf loss waste. A medium-scale acid leaching procedure is depicted in Fig. 15. By treating with mixed acids solution (1 M HCl/HF/H2SO4), over 94% of the metallic impurities was eliminated. Under the condition of 1 M HNO3 solution, nickel impurity was further removed, but the oxygen concentration was increased to nearly 10 wt%. As the boron and phosphorus contents in the raw materials were low, they were decreased to sub-ppmw levels, with a removal fraction of 70% after the acid leaching process. The removal efficiencies of the metallic impurities in different acid solutions were compared. Nickel was reduced to 2.7 and 8.6 ppmw from 135 ppmw with the use of small-scale and medium-scale acid leaching processes, respectively. Besides, it was noted that HF solution is more effective than other acid solutions on Ni removal. B and P were decreased to sub-ppmw and C was reduced to several hundred ppmw, while O was less than 5 wt%.

Yang et al. [76] investigated the dissolution and mineralization behaviors of metallic impurities in the diamond wire saw waste using external-field (microwave and ultrasound) and lixiviant-assisted acid leaching process. The results indicated that the acid leaching dissolution processed from the surface to the core, following a shrinking core model. The SiO2 layers on the surfaces of the particles prevented the leaching of interior. A total removal efficiency of 99.28% was obtained using the optimum mixture solution (4 M HCl + 0.5 M HF) with external-field assisted acid leaching treatment.

3.2.2. Hydrobromination method

Tomono et al. [28,82] proposed a hydrobromination method to purify Si from kerf loss Si waste. The principle is that Si reacts with HBr to form tribromosilane (SiHBr3) and tetrabromosilane (SiBr4) at a certain temperature. The formation equation of bromosilanes can be expressed as follows [83]:

$$\text{Si} + n\text{HBr} = \text{SiH}_{n+3}\text{Br}_n + (n - 2)\text{H}_2$$  \hspace{1cm} (1)

Subsequently, the bromosilanes were hydrolyzed to silica through the reaction with water vapor in the air, as follows:

$$\text{SiH}_{n+3}\text{Br}_n + 2\text{H}_2\text{O} = \text{SiO}_2 + n\text{HBr} + (4 - n)\text{H}_2$$  \hspace{1cm} (2)

Fig. 16 presents the flow chart of the reaction system for the hydrobromination of Si. The kerf loss Si waste, with and without abrasive SiC particles, was initially heated to 400 °C under N2 atmosphere. Later, a gas mixture (N2 30 mL/min and HBr 10 mL/min) was injected into the reaction tube and measured using an online gas chromatography instrument.

The effluent gas was passed through a condenser maintained at -40 °C. Because of the boiling point difference, SiHBr3 (b.p. 118 °C) and SiBr4 (b.p. 153 °C) were changed into a liquid state. Simultaneously, HBr (b.p. -66 °C) and N2 (b.p. -196 °C) were transformed into a gaseous state accompanied with the unreacted gases and passed through out. The liquid samples were hydrolyzed and formed SiO2 with water vapor in the air. This method is suitable for the brominated species possessing higher boiling points than the reaction temperature. Because SiC does not react with HBR and possesses higher thermal diffusivity (1.28 × 10^{-8} m^2/s) than Si (9.34 × 10^{-8} m^2/s) [84,85], it is assumed that these particles can promote the conversion efficiency of the reaction between Si and HBr. Moreover, some inclusions, such as aluminum, iron, nickel in the Si waste could react directly with HBr to form brominated compounds (eg. AlBr3, FeBr3, and NiBr2), and the other impurities, such as copper, remained on the Si bed [28]. Although AlBr3, FeBr3, and NiBr2 were also produced, their high boiling points AlBr3 (b.p. 265 °C), FeBr3 (b.p. 934 °C), made them remain inside the reaction tube or reactor in the form of residues. After the reaction, Al, Fe, and Cu are reduced obviously. Removal fractions of Al, Fe and Cu were 99.23%, 94.86% and 50%, respectively. These results demonstrate that the hydrobromination method is effective in purifying Si from the Si waste even in the presence of SiC.

3.2.3. Aerosol method

The carbon present in the kerf loss Si waste can be removed by the aerosol method. Jang et al. [86] reported an ultrasonic aerosol spray-drying method to obtain nano-sized Si particles from sludge Si waste. The schematic diagram of the ultrasonic aerosol-assisted Si extraction process is shown in Fig. 17. First, the dried slurry powder was washed with hydrochloric acid solution to remove the metallic inclusions. The powder was dispersed in distilled water and stirred to obtain a colloidal suspension under ultrasonication treatment to recover the nano-sized Si particles from the Si-SiC mixture. During ultrasonication process, the dried Ar gas with a flow rate of 0.5–2.0 L/min was injected into the reservoir, and the ultrasonic atomizer was utilized to transport the aerosol droplets into a vertical tube furnace pre-heated to 300–500 °C. At last, the dried Si powder was collected by a filter under vacuum. The results asserted that 80 wt% of Si with a size range of 0.1–1.5 μm was separated from the Si slurry waste by the ultrasonic aerosol process, and that only 3.8% SiC remained in the recovered materials. The residue sample was mainly composed of SiC particles ranging from 2 to 20 μm.

Miguel et al. [87] conducted a similar study that applied the ultrasonic aerosol method to remove carbon from the kerf loss Si waste. In their research, two different atmospheres were employed in the aerosol process. From the literature, the removal fraction of C was 90% at 900 °C in N2 atmosphere. The mean residence time was found to be 0.09 min in the furnace. Under the same conditions in the presence of air, the C content was reduced below the detectable level with a residence time of 6 s. When compared with the air condition, minimal oxidation of the Si powder was observed. These results establish that the ultrasonic aerosol spray-drying method is a promising route to prepare nano-sized Si particles from the kerf loss Si waste. However, because of the intensive energy consumption, this production process is restricted to large-scale recycling applications.

3.3. Metallurgical method

3.3.1. Alloying method

Wang et al. [88] proposed a Si-Al alloying process to separate Si and SiC from the kerf loss Si waste. The waste was mixed thoroughly with aluminum powder in a quartz crucible and heated at 1773 K for 1 h under Ar atmosphere to produce Al-Si ingot phase. The X-ray diffraction patterns of the Si waste before and after the alloying process established that SiC had been completely removed and that an Al4C3 phase with a hexagonal crystalline structure in the range of 0.1–2 mm diameter had been formed on the top surface of the Al-Si ingot as shown in Fig. 18. This change is attributed to the formation of the Al4C3 phase through the below mentioned reaction [89]:

$$4\text{Al} + 3\text{SiC} = \text{Al}_{4}\text{C}_{3} + 3\text{Si}$$  \hspace{1cm} (4)

From the literature [88], the Al-Si hypoeutectic phase was formed on the top of the ingot with the bottom contains Al-Si hypereutectic phase, which shows that liquid Al is effectively to alloy with the Si in the waste. Furthermore, Large Si particles in the form of primary Si were observed at the bottom of the alloy sample. Impurity carbon was introduced to the Al-Si alloy on the top of the ingot in the form of Al4C3 phase, but it was removed after polishing treatment. Even though this work provides a novel way to separate Si and SiC from the kerf loss Si waste by the alloying method, the parameters were not optimized as
part of the study.

3.3.2. Slag refining method

Slag refining treatment is a feasible route to remove the impurities associated with Si, especially for boron and aluminum. The impurities were oxidized and then trapped by the slag regents, thus purifying the Si [21,90]. Huang et al. [21,81] used Na$_2$O-SiO$_2$ slag refining extract and purify the Si from the kerf loss silicon waste. A schematic diagram

![Fig. 16. Flow chart of a reaction system for hydrobromination of Si [28].](image)

![Fig. 17. Flow chart of the ultrasonic aerosol assisted Si extraction process [86].](image)

![Fig. 18. Morphologies of Al-Si ingot (a) Al-Si ingot; (b) top surface of Al-Si ingot; (c) SEM image of top surface of Al-Si ingot; (d) SEM image of bottom surface of Al-Si ingot; (e) XRD patterns of the samples [88].](image)
of slag refining of the kerf loss Si waste is shown in Fig. 19. At first, the Si waste and slag were mixed thoroughly and loaded in a graphite crucible and heated at 1750 °C for 3 h and cooled to room temperature. The Si bulk was ground to particles less than 1 mm in size and acid leached with 2 M HCl solution with the help of a magnetic stirrer. The parameters for the acid leaching reaction were as follows: room temperature, holding time of 12 h and solid/liquid ratio of 1:10. In the contrast experiment of the kerf loss Si waste with slag refining treatment, direct leaching was done under the same conditions. It was found that the total content of the major impurities (B, P, Al, Ca, Fe and Ni) were reduced from 6998 ppmw to 58 ppmw with a total removal fraction of 99.2%. The purity of the refined Si increased to 99.98% from 93.3%. According to the Ellingham diagram of oxides, the oxygen affinities of boron, aluminum and calcium are stronger than that of iron and phosphorus [91]. Therefore, boron, aluminum and calcium are easier to be removed by the slag refining treatment, while the removal efficiencies of iron and phosphorus are limited. The optimum condition by Na2O-SiO2 slag refining at 1923 K were determined: the slag composition was Na2O-35 %SiO2 and the treatment time was 30 min s [21]. The boron content was reduced from 88.6 ppmw to 1.0 ppmw, and the mass transfer coefficients for B in Si and slag were found to be $3.6 \times 10^{-6}$ cm/s$^{-1}$ and $5.9 \times 10^{-6}$ cm/s$^{-1}$, respectively. This work describes an effective strategy of obtaining high purity Si from the Si waste.

Li et al. [92] applied the electromagnetic force-assisted slag refining treatment to separate and purify Si from the kerf loss Si waste. The slag and Si waste and CaO-SiO2-Na3AlF6 slag were placed in the induction furnace with a power of 17.5–20 kW and holding time of 45 min. The substances in the solid kerf loss Si waste were mainly Si and SiC particles, and the impurity elements include carbon, aluminum, calcium, iron, phosphorus, boron, oxygen, etc. The CaO-SiO2-Na3AlF6 slag in the refining process can improve the separation efficiency of Si with a purity of 99.47%. After the slag refining treatment, B and P were reduced to 5.13 ppmw (91.05% removal fraction) and 24.21 ppmw (30.55% removal fraction), respectively, using CaO-SiO2-Na3AlF6 slag. As for the metallic impurities, the removal fraction of aluminum reached 91.67% in the refined Si, whereas the removal efficiencies of nickel and iron were not high enough. As a result of this treatment, the purity of the refined Si increased to 99.47% from 88.01%, and it was further improved to 99.98% by using a vacuum direction solidification process.

During the slag treatment, the Si particles are inevitably oxidized to form SiO2 layers on the surfaces, which causes a certain amount of Si loss. Up to 8% of the Si was present in the form of oxide in the sawing waste. The Si loss was inevitable during the slag refining process, but the SiO2 layers coated on the Si particles effectively provided the necessary oxygen potential to oxidize B into the slag phase [93]. The slag refining mechanism of the Si waste was elaborated. At first, the slag reacts with the surface SiO2 layer to form a melt, which then mixes with other liquid phases in the rest of the powders. At last, the non-conductive SiC particles and some other oxides are physically aggregated and separated from the Si melt phase under electromagnetic force, as schematically illustrated in Fig. 20. Moreover, most of the impurities, such as C, B and O, react with the slag fluxes. All these reactions improve the oxidation of the impurities, which makes the oxides enriched in the outer slag phase. One shortcoming of the slag refining is that the operating temperature is high (usually $> 1414^\circ$C) and depends on the melting point of the applied slag. Furthermore, the incomplete physical separation of the refined Si from the residual slag and the oxidation of Si by the slag regents result in obvious Si loss, hindering its commercial application.

3.3.3. Induction smelting method

Electromagnetic induction smelting is a feasible and environment-friendly way to remove non-metallic impurities or inclusion phases from a molten alloy or metal by using electromagnetic force. The advantage of this technique is that it does not introduces many additional impurities from the external environment [94,95]. Kong et al. [78] applied this strategy to recover and purify the Si value of the silicon waste powder received from the multi-diamond-wire sawing process. Prior to smelting, the silicon waste powder was leached in H2SO4 solution (25 wt%) to remove most metallic impurities. The leached product was fluxed with 13.5 wt% silicon oxide and smelted at 1773 K in an induction furnace to remove B and P. After solidification, the refined Si ingots with a purity of Si 99.99%, P with 1.1ppmw and B with 0.16ppmw were obtained.

Jiang et al. [96] applied a supersonic-frequency magnetic technology to separate SiC inclusions from the Si waste. Under the high-frequency magnetic force, inclusions such as SiC have a tendency to migrate to the boundary of the Si ingot as the holding time increases. During the smelting process, the fine SiC powders can be evaporated by combining them with the Si powder in the gaseous environment. The evaporated SiC powders get deposited on the Al2O3 cover. The penetrated aluminum dissolves the SiC powders [97], which can augment the separation efficiency to 89.3% when the holding time is increased to 45 min.

These results suggest that the use of supersonic frequency magnetic field on SiC inclusion removal holds immense potential under the induction melting process for the recovery and recycling of the Si waste. Fig. 22 depicts the separation of SiC inclusions from the Si waste by using the induction smelting process [96]. The SiC inclusion experience a process of sedimentation-settling and then dissolved by the penetrated
aluminum. The removal efficiencies of inclusions are improved by applying a relatively low frequency magnetic field with a shorter holding time.

3.3.4. Plasma refining method

Plasma refining technology possesses the special characteristics of high energy density ($10^6$–$10^7$ J/m³), high flux density ($10^7$–$10^9$ W/m²), high processing efficiency and wide choice of reactants ($10^5$–$10^8$ K/s) [98]. Thermal plasma melting method has been utilized to purify metallurgical grade Si and Si waste [99,100].

Sousa et al. [101] utilized a two-step thermal plasma process to obtain high purity Si from the Si slurry waste. A gas (Ar or Ar-H₂ mixture) was injected into a non-transfer arc-plasma furnace with a velocity of 1000 m/s and a temperature of 12,000 K [102]. The kerf loss silicon powder was pre-oxidized at 1473 K for 3 h in an air atmosphere and then injected into the plasma jet with a velocity of 190 m/s and arc current of 600 A. After plasma processing, particles ranging from 0.5 to 10 μm were gas quenched in a neutral atmosphere and collected as an ingot at the bottom of the crucible, as shown in Fig. 23. The parameters such as plasma gas composition (Ar gas with low hydrogen content < 5 vol%), flow rate (130–745 m/s) and nozzle diameter (10–12 mm), were investigated. After purification, the removal rate of SiO₂ reached 80% and the concentration of C decreased by 85%. In the plasma refining process, Ar-H₂ mixture exhibits high thermal conductivity and specific enthalpy, which makes it feasible to maintain the molten bath of Si with high plasma jet velocity. Large enthalpy input increases the vaporization rate of the powder and decreases the yield of the refined
Oh et al. [99] applied a hydrogen plasma arc melting process to purify the Si waste. An ultra-high-purity Si ingot was obtained (99.9999%), and the contents of boron and phosphorus were reduced to 0.102 ppmw and 0.115 ppmw after three cycles of treatment, respectively. These results meet the purity requirement of solar cells. However, several issues still need to be addressed with regard to the plasma refining process. First, it was difficult to inject fine particles less than 10 μm in size into the plasma jet with high velocity and momentum. Second, the extremely short dwelling time, i.e., less than 1 ms, makes it difficult to control the reaction taking place in the hot core of the plasma jet. Third, the refined Si powder is oxidized slightly again due to an oxygen potential in the furnace. Fourth, the thermal plasma is an energy-intensive strategy, which requires a significant amount of electricity. Based on the processed power, the energy consumption of the plasma treatment was estimated to be 80–1000 kWh/kg. In fact, the effective reaction area was only about 20 cm³. The thermal plasma requires a large amount of electricity, which is one of the most expensive forms of energy. High energy consumption and low yields frequently result in unfavorable economics for large-scale applications. The processing of the Si waste particles injected into the plasma jet depends not only on the energy density of the plasma and the capacity to transfer it to the powder but also on the dwell time of the Si waste powder in the hot zones.}

Si.

3.3.5. Rapid thermal process method

Yang et al. [103] utilized a rapid thermal process (RTP) to remove the impurities from the Si waste. The effect of heating rate (~40 °C/s), temperature variation (1420–1500 °C), holding time (1–8 min), and cooling rates (0.167 and 40 °C/s) were studied. In the first stage, the Si particles began melting and agglomerated from the solid Si waste within 3 min. Moreover, the fine SiC powder and metallic inclusions migrated easily to the surface of agglomerated Si, as shown in Fig. 24. In the second stage, the impurities such as SiC and metals present on the surface of agglomerated Si were eliminated by acid solution (with the ratio of HF: HNO₃ = 1:3). Subsequently, the excessive oxides were removed using HF solution (50 wt%) for 60 s. The rate of the rapid thermal process was one hundred times higher than that of the other high-temperature metallurgical processes [5,11]. Metallic impurities, such as Fe, Cr, Cu, Ni, Ca, V, Ti and Ta, mainly migrated to the top of the agglomerated Si. Besides, SiC powders were also observed at the wall of the crucible at slow cooling rates. High purity Si agglomeration was obtained using a further surface acid etching process, and the highest recycle yield was more than 70%.

The rapid thermal method shortened the processing time under Ar atmosphere, and the Si agglomeration easily made the SiC powder and metallic inclusions segregate to the Si surface. However, it was difficult to control the yield of purified Si was not easy to control because of the oxidation of the ultra-fine Si particles during the rapid thermal process. Miguel et al. [104] explored the carbon removal from kerf loss Si
waste by high temperature treatment in two atmospheres: air and nitrogen. In their work, the carbon source chiefly consisted of polyethylene glycol (PEG), diethylene glycol (DEG) and lubricant. Two different carbon elimination mechanisms of the kerf lubricant under the conditions of air and nitrogen were proposed based on the actual thermal decomposition of the organic lubricant in the Si waste. As seen in Fig. 27, in the first stage, the reaction rate was dominated by the long hydrocarbon chains undergoing depolymerization by rupture of the C-C and C-O bonds in competition with further polymerization. During the second stage, the performance varied with the atmosphere used. In the presence of air, the energy demand of the depolymerization was less, and the polymerization of the carbonaceous compounds was not effective in facilitating the organics removal. Complete removal of C in nitrogen atmosphere was not achieved under the temperatures and the heating rates used. The final removal fraction of carbon was 88% in N₂ atmosphere. On the contrary, the removal rate of carbonaceous compounds was higher in air than in N₂ atmosphere. However, this efficiency was achieved at the cost of Si oxidizing, which is undesirable in the kerf loss Si purification.

3.3.6. Vacuum refining method

Vacuum melting method is a way of removing the impurities possessing vapor pressures lower than that of Si [105,106]. However, the Si waste powder will generate a huge loss and result in a low yield of Si. To increase the yield of the purified Si and remove the impurities such as C and other metals, some assisted methods were proposed under the vacuum melting process. Two different routes are shown in Fig. 25. Laser granulating assisted technology was introduced to solve the melting problem of the Si powder and improve the yield by Lu T. et al. [107]. In the first stage, the kerf loss Si waste powder was rapidly fused into one irregular sphere by laser granulation process. The parameters of power, scanning rate and scanning interval were 2000 W, 6 mm/s, and 2, 5 and 10 mm, respectively. In the second stage, the Si blocks were vacuum melted at 1450 °C for 30 min under the 2.5 × 10⁻³ Pa. The yield of the Si bulk was over 97% at a laser power of 2000 W. The removal rate of C reached 86% after executing the vacuum refining process.

Non-transfer arc assisted vacuum smelting method is another effective way to improve the yield of purified Si from the kerf loss Si waste [108]. Under the condition of scanning speed of 5 mm/s, output power of 7.5 kW, the output capacity of the Si bulk was 0.96 kg/h and the energy consumption of the non-transfer process was 14.87 kWh/kg. These values are much higher than that obtained with the laser melting process (2.63 kWh/kg). The removal rate of carbon in the purified Si was 71% after the non-transfer arc granulating process. The final yield and filling rate of Si were 96% and 73%, respectively, after the vacuum direction smelting process at 1450 °C and 4 Pa for 30 min. During the non-transfer arc granulating process, no additional impurities were introduced, and most of the metallic impurities were effectively eliminated. This method provides a new and efficient research direction for the high-energy–density powder granulation and purification technology.

3.3.7. Carbothermic reduction method

Liu et al. [80] reported a carbothermic reduction process to obtain purified Si from the kerf loss Si waste. The pretreated dried kerf loss waste and high purity SiO₂ were mixed with a binder (carboxymethyl cellulose) and introduced into an electric arc furnace at a temperature range of 1900–2000 °C and a power of 15–25 kW. The effects of SiO₂ particle size (micro-SiO₂ and nano-SiO₂) and SiO₂/SiC ratio on the Si purification were examined. The results demonstrated that silicon and silicon carbide were completely separated by the carbothermic reduction process. The purity of the obtained Si was 99.15% and it had low concentrations for boron (0.06 ppmw) and phosphorus (0.24 ppmw), which fulfilled the requirements for solar grade silicon. When comparing the micro-SiO₂ and the nano-SiO₂, the purity of Si within the 10% micro-SiO₂ (99.15%) was much higher than that within the 10% nano-SiO₂ (97.65%). The nano-silica particles had a larger internal diffusion resistance and specific surface area than the micro-silica particles. The ultra-fine silica particles exerted negative effect on the flow rate of gaseous SiO and restricted the permeability of the gas. The schematic diagram of the reaction in the electric arc furnace is provided in Fig. 26. Silica reacted with SiC or Si to transform gaseous SiO and CO. The silica and silicon melt descended downwards because the hottest temperature occurred at the bottom of the furnace. Meanwhile, some SiC powder reacted with SiO and formed CO or Si. The unreacted SiO and CO moved upwards in the electric arc furnace. These results establish that the carbothermic reduction process can be effectively used for the separation of high purity Si from the kerf loss Si waste.

To decrease the reaction temperature of the carbothermic reduction, a vacuum assisted method was introduced to separate the high purity Si
from the Si waste powder by Yang et al. [109]. In their research, the amorphous SiO₂ and the Si core-silica shell structure were ground evenly and pressed at 30 MPa to form a cylindrical cake, which was heated up at a rate of 15 °C/min to reach a temperature of 1300–1700 °C. The pressure in the furnace was maintained in the range of 1.1 × 10⁻¹–2.2 × 10⁻² Pa for 3 h. The liquid Si core melt was dissociated from the amorphous silica layer with the collapse of the Si core/silica shell. Then, the Si particles agglomerated under the high temperature. Moreover, the amorphous silica shell was attacked by the activated C powders from the graphite rod and deoxidized by the vacuum carbothermic reduction process. Subsequently, the silica particles were transferred to the Si droplets. From the literature [109], it could be deduced that vacuum treatment can indeed decrease the refining temperature of the carbothermic reduction of silica. This decrease can in turn result in lowered unit energy consumption when compared with the conventional carbothermic reduction process.

Based on the overview of different high temperature metallurgical methods, it can be concluded that they tend to differ in their characteristics for the removal of various impurities. The detailed comparison of impurities removal with different high temperature metallurgical methods is provided in Table 5. All these processes require temperatures higher than 1414 °C (the melting point of Si); correspondingly, the energy consumption is larger than that of other physicochemical methods. However, from the perspective of impurities removal, most of the metal impurities can be eliminated to a great extent by this method than is possible through other chemical or physical methods. Especially, the contents of boron and phosphorus can be decreased to the level of solar grade Si by certain metallurgical methods. As for the diamond abrasive sawing waste, the removal fraction of carbon was close 100% by the alloying method.

### 3.4. Other method

The slicing wire used in the sawing process is made of drawn steel coated with diamond/Cu powder with diameter in the range of 100–140 μm [110]. Schwinde et al. [111] investigated the wear condition and the diameter of the wire during the sawing of virgin and worn wire samples. A potentially feasible method for the reduction of the Si kerf loss and the consumption of wires was put forward, which applied a non-circular cross-sectioned wire by adjusting the grooves in the wire guide rolls. The geometry of the non-circular grooves avoided the over-turning of the slicing wire and ensured that it was in an upright orientation towards the Si ingots. By keeping the cross-sectional area of the slicing wire constant, its mechanical strength was kept stable and the risk of breakages was reduced. In comparison with the circular cross-sectional slicing wire in Fig. 28, because of the increase in the

![Fig. 26. Schematic drawing of carbothermic reduction process [80].](image1)

![Fig. 27. Two-step mechanism for carbon elimination in slicing lubricant [104].](image2)
upright axis, the abrasions of the steel slicing wire coated with diamond particles were intensified by reducing its relative length per wafer. This work signifies another potential way to reduce the kerf loss waste and decrease the manufacturing cost of solar cells.

4. Application of kerf loss Si waste

The recovery and recycling of high purity Si and other inclusions from the kerf loss Si slurry waste exhibits great value on the aspect of environment and recycled economy. At present, several efforts have been taken for the recycling and reuse of the Si waste. The main application fields of the Si waste as shown in Fig. 29, include photovoltaics, lithium ion batteries, photocatalyst, electrocatalyst, mullite ceramic, nano materials, thermoelectrics etc. which show good performance as well as sustainability.

4.1. Electrocatalytic materials

The development of electrocatalytic materials possessing the characteristics of high catalytic activity and affordability is an important

![Diagram](image-url)
research field. These materials could potentially replace the Pt-based fuel-cell catalysts [112]. Tsai et al. [53] applied the submicron-sized Si-rich particles from the kerf loss Si waste to prepare an electrocatalyst. The pre-treated Si powder (85% Si and 346 ppmw Fe) was mixed with carbon Vulcan XC-72 and applied in a methanol electrooxidation field. The Si-rich particles exhibited great potential for electrocatalytic application of the methanol electrooxidation. The current density of the Pt/C/Si-rich catalyst was larger than that of the Pt/C catalyst, which indicates that the Si particles may be a suitable choice to recycle the Si powder from the kerf loss Si waste.

4.2. Photocatalytic materials

The use of hydrogen as a clean and renewable energy carrier has attracted increased attention owing to the issues of energy crisis and environmental pollution. Photocatalytic water decomposition is an ideal and renewable way to extract hydrogen under irradiation of sunlight [113]. The Si waste from the PV industry, which contains a high concentration of purified Si and SiC powders, is a promising candidate to realize the dream of low-cost H2 production [114]. Zhang et al. [115] used separated SiC particles from the Si waste as a photocatalyst to produce H2 in the presence of Na2SO3-Na2Si. The initial particles were dispersed in NaOH solution and maintained for more than 12 h at 80 °C until the Si particles were completely reacted with NaOH. The highest H2 production rate was 191.8 mol/h·g, and it occurred when the content of doped Pt was 1 wt%. A feasible mechanism for photo-catalytic reaction was proposed. This work provides a way to recycle the separated SiC powder from the Si waste discharged by the PV industry and reuse it as a type of photocatalytic material to produce H2. The method has the advantages of low energy consumption, low pollution and ease of operation.

4.3. Lithium ion battery materials

Si, one of the most attractive and promising next generation anode materials, has been investigated intensively in the lithium ion battery field, because of its high theoretical specific capacity [116,117]. When compared with commercial graphite anode materials, the specific capacity of Si (Li22Si5 4200 mAh/g) is much larger and is ~10 times higher than that of the graphite present in lithium ion batteries. Some commercial lithium ion batteries have been doped with small quantities (~5%) of nano-silicon particles. The lithiation of Si occurs at low potentials vs. Li/Li⁺ resulting in the low operating voltage of the Si anode (0.4 V vs. Li/Li⁺) [118].

Jang et al. [86] applied Si nanoparticles from the kerf loss Si waste to prepare lithium ion battery anode materials. The separated nano-Si particles in the anode exhibited better capacity retention than the commercial nano Si powder owing to the ample free volumes at different length scales. Wanger et al. [119] reported that the cycle life at a capacity of 1000 mAh/g can reach over 300 cycles in a half-cell experiment. The specific capacity can reach up to 150 mAh/g in a full-cell testing against an NMC 442 cathode. This is also a relatively low-cost tactic to utilize the kerf loss Si waste and increase the value of the waste.

4.4. Thermoelectric materials

The use of recycled Si waste in thermoelectric applications has also been adopted as a potential strategy to reduce environmental pollution. In the field of thermoelectric materials, a key point in their widespread application is the development of less expensive and earth-abundant materials [120,121]. Silicide compounds have the advantage of non-toxicity, ample availability and environment-friendly nature, thus gaining wide popularity. He et al. [122] reported the thermoelectric properties of separated Si from the kerf loss Si waste. The results suggested that a peak ZT of ~0.33 and a peak PF of ~32 μWcm⁻¹K⁻² at 1273 K were reached in heavy P doped Si powder. The obtained PF was comparable with the phosphorus-doped Si-Ge alloys used in modules for power generation application. Mesaritis et al. [3] synthesized Mg2Si based thermoelectric materials using recovered Si powder from the kerf loss Si waste at 800 K. Bi and Sb doped Mg2Si1-x-ySnxGe y materials displayed a high thermoelectric performance. The presence of SiC in the thermo-electrics increased the lattice thermal conductivity. Metallic particles in the matrix contributed to the power factor increase, with a high ZT of 1.3. These results certify the immense potential of using recycled Si waste in thermoelectric applications.

4.5. Porous/mullite ceramic materials

Porous ceramics, with the characteristics of large specific surface area, high porosity, chemical stability and low thermal conductivity, can be applied in several fields [123,124]. Zhou et al. [125] used the kerf loss Si waste to make porous ceramics by foam-gel casting method. The morphologies of the fabricated porous ceramics are shown in Fig. 30. The porosity of the ceramics was 86.7%, and the thermal conductivity was 0.178 W/(m·K) [125]. These properties are conducive for their application in the thermal insulation field.

Li et al. [126] used the Si kerf waste sintering additives to produce Si1-xN y ceramics at 1723 K. The results indicated that the bulk density of the ceramics increases, and the apparent porosity decreases with an increase in the use of the sintering additives (Al2O3 and Y2O3), which could improve the strength of the ceramics. When the additives content was 2%Y2O3 and 5%Al2O3, the highest strength of 120 MPa was reached.

4.6. Nano-silica materials

Nano-silica particles can be widely applied in the fields of sunscreen cream, rudder products, refrigerator shell, printing ink, paste product, computer keyboard, paint and coating, etc. [127,128]. The properties of dispersion, thixotropy and thickening not only improve the intensity of rubber tearing, toughness and wear-resisting but also increase the clarity of the print. Ding H. et al. [32] applied sodium hydroxide to dissolve Si in sodium silicate solution, and the SiC particles were separated by a filtration process. Subsequently, the nano-sized SiO2 particles were produced by the acid precipitation method using HCl solution. High purity amorphous SiO2 powder, with an average size of 10.52 nm and high specific surface area of 430.9 m²/g was obtained.

5. Conclusions

This paper presents a literature overview of the research progress on the recovery and recycling of high purity Si and other inclusions from the kerf loss Si waste in the PV industry. Based on the above review, the authors assess the current routes to recover Si from the Si wastes and...
provide an outlook for further research.

5.1. Evaluation of technologies

A variety of methods for the effective separation and recovery of high purity Si from the Si waste have been overviewed in this work. The compositions of the kerf loss Si wastes are different from each other owing to the variations in the crystalline Si sources and slicing processes. Therefore, it is necessary to identify and characterize their structures and compositions in advance. The appropriate processing method depends on the forms of occurrence and the distribution of impurities or inclusions in the initial kerf loss Si waste materials. The flow chart depicting the comprehensive recovery and reuse of the recycling kerf loss Si waste is shown in Fig. 31. From the perspective of recovery technologies of Si, solid (Si-SiC/diamond) and liquid (mainly PEG solution) wastes should be separated at first. Centrifugation, gravity separation, filtration, etc. are common and effective strategies for solid–liquid separation. These methods can be executed at room temperature, thereby resulting in a relatively lower energy consumption when compared with the other high temperature treatments. However, the limitation is that these methods only effectively applied for solid/liquid separation.

Acid leaching is an effective way to remove metal impurities such as Fe, Al, Ni and Cr, via active reaction with the acid solution. In this work, the authors compared the removal fractions of impurities using different acid solutions. Over 90% of the metals were effectively removed from the Si waste. Both diamond and SiC are inert and acid-resistant during the acid leaching process, and hence remain with the Si powder after the elimination of the metal impurities. Some physical methods (hydrocyclone method, electrical method, phase-transfer method, supercritical method, etc.), chemical methods (flotation method, aerosol method, etc.), and high temperature metallurgical methods (alloying method, slag refining, induction smelting, thermal plasma melting, vacuum refining, carbothermic reduction, etc.) have been introduced to separate Si and SiC based on the characteristic of the mixture of the kerf loss Si waste.

The physical and chemical methods have a relatively lower operation temperature, but their removal efficiency is also lower when compared with the high temperature metallurgical processes. On the contrary, most of the metals in the Si could be removed by high temperature metallurgical methods. Each process has its own advantages as well as limitations. Hence, their suitability should be comprehensively investigated before applying them in separation and purification. Besides, the parameters should be carefully optimized to enhance the process efficiency.

5.2. Evaluation of Si waste recycling

Recycling of the kerf loss Si waste involves many aspects, such as resource, cost, environment, energy, economy, sustainability, etc. as shown in Fig. 32.

- Si is an important resource for the PV application. More than 90% of the solar cells are produced from crystalline Si. Manufacturing of high purity Si is an energy-intensive process. The cost of recycling of the solar grade Si wastes is only ~5% of that of the primary production. Therefore, the recycling of Si waste could reduce the loss and increase the utilization of the element.

- Cost is an important factor which influences the recycling of the Si waste. From the perspective of ingot production, increasing the mass of the Si ingots could reduce the production of the Si waste. Other effective methods include modifying the slicing process, such as reducing the diameter of the wire, homogenizing the diamond particles, etc., which would also reduce the production of Si waste and improve the surface smoothness of the Si wafers.

- Fine Si waste powder easily reacts with water to form hydrogen, which will generate explosive hazard and cause a negative impact on the environment. Also, the slurry waste will result in water and air pollution if not treated. Therefore, the classification of different Si wastes should be identified, and they should be recycled using a low carbon technology to reduce CO2 emission.

- Energy consumption and economic factors also play a pertinent role
in the recycling of Si waste. On the one hand, we should utilize clean and renewable technologies and develop comprehensive methods; on the other hand, we should improve the energy efficiency and extend the application fields, such as electrocatalyst, photocatalyst, lithium-ion batteries, ceramics, etc.

5.3. Outlook

Large quantities (> 200,000 tons) of the kerf loss Si powder are deposited as waste every year. The concept of separation and recovery of the high purity Si and other inclusions from the kerf loss Si slurry waste has been researched extensively, and some new technologies have been developed. Recycling the Si waste is of great importance since the demand for solar cells is increasing. The recycling of the Si waste has a positive influence on the environment. The energy consumption for the recycling process is considerably lower than that of conventional Si purification. Thus, recycling of the Si waste is potentially beneficial in reducing the CO₂ emissions. The recovered high purity Si exhibits good performance in different application fields. However, the cost associated with the recycling of Si waste remains to be the critical point, which restricts its large-scale application. To achieve the best possible results in a cost-effective manner, more innovative, economical and feasible approaches need to be explored. The new technologies not only save the expenses involved in recycling of the Si waste but also alleviate the pollution problems. It is clear that a few challenges (e.g. economic feasibility, separation efficiency of more valuable materials and recovery of high purity Si), still remain in process efficiency, complexity and energy requirements for the treatment.

Fig. 31. Flow chart of comprehensive separation and recovery of kerf loss Si waste.

Fig. 32. Recycling evaluation of kerf loss Si waste.
Declaration of Competing Interest

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

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