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Exploration on how could Chinese PV module recycling companies scale up a new recycling technology

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Abstract

As of 2021, China's newly installed photovoltaic (PV) capacity has topped the world for nine consecutive years. Considering that the general life of crystalline silicon PV modules is 25 years, in the near future, China will face a wave of decommissioning of waste PV modules. Therefore, it is crucial to develop and improve China's PV module recycling industry in advance. Based on TIS framework, this thesis analyzes how to make module recycling spread in China from the perspective of PV module recycling enterprises. The main content of the research is divided into two parts: the first part collects literature, reports and news related to PV module recycling technologies, and puts different technologies into the established evaluation system for evaluation, so as to obtain the best performing technologies. In the second part, information related to China's PV module recycling technology and industry is collected through desk research and interviews, and the status of each building block and influencing conditions in TIS framework is analyzed. On this basis, the barriers to the large-scale diffusion of PV module recycling in China are found, and the corresponding strategies that need to be adopted by all parties are also developed. The research results of this thesis show that the mechanical delamination of PV modules and the hydrometallurgical technology for valuable metal recovery are the most promising combination of PV module recycling technologies. At present, there are four main barriers to the large-scale diffusion of PV module recycling in China. First, the level of recycling technologies used by enterprises are uneven, and there is a lack of core technologies for large-scale treatment and disposal of pollutants generated by recycling. Second, it is not clear what to do with the valuable materials obtained after recycling. Third, China's PV module recycling market is very chaotic, lack of fair competition. Fourth, there are still gaps in key policies and standards, including subsidies and policies to regulate market order, as well as standards to judge whether PV modules are abandoned. Removing these barriers will require different types of actors in the industry. PV module recycling enterprises need to continuously explore and improve the module recycling technologies and supporting technologies. At the same time, they need to determine what to do with the recovered valuable materials. In addition, the Chinese government needs to formulate a subsidy policy for research and development and investment related to PV module recycling. Also, policy gaps to regulate market order should be quickly filled. The National Standardization Administration needs to issue the standard for judging the waste of PV modules as soon as possible.

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Abbreviation	Explanation
PV	Photovoltaic
TIS	Technological Innovation System
MC	Multiple criteria
MFA	Material flow analysis
EOL	End-of-life
c-Si	Crystalline silicon
LCS	Life cycle symbiosis
TCE	Trichloroethylene
MIIT	Ministry of Industry and Information Technology

1. Introduction

As a clean and reliable renewable energy technology, PV power generation has gained more and more attention. In 2021, PV capacity increased by a record 179 TWh, a 22% increase over the previous year. Meanwhile, PV accounted for 3.6% of global power generation that year (International Energy Agency, 2022b). By 2027, solar PV will overtake coal in installed capacity and become the most important source of power generation, according to projections (International Energy Agency, 2022a).

China's PV industry has experienced a long period of development. After going through the initial stage and demonstration and promotion stage, China's PV market entered the stage of large-scale development in 2013 (Yao, 2019). In 2021, China's cumulative installed PV capacity has topped the world for seven consecutive years, and its newly installed PV capacity has topped the world for nine consecutive years (China Photovoltaic Industry Association, 2022). By the end of the year, the newly connected capacity reached 54.88 GW, and the cumulative connected capacity reached 305.98 GW (National Energy Administration, 2022a). It can be said that China's PV industry is leading the world in terms of installed capacity and growth rate. However, PV modules typically have an expected life span of about 25 years, which can be lower when subject to a variety of natural factors (Aghaei, 2022). As a result, the total amount of waste PV modules in China will explode after 2030 and increase year by year. Therefore, it is worth thinking about how to efficiently and cleanly recycle these waste PV modules. Once a complete recycling pipeline is formed, it will bring huge economic and environmental effects to China's PV market.

Considering that silicon solar modules still occupy more than 90% market share (Tao, 2020), this thesis will focus on the recycling technology of such modules. The recycling of silicon PV modules can be divided into two types: downcycling and upcycling (Deng, 2019). Downcycling is mostly mechanical disassembly and landfill. Although the process is simple, the economy is poor (Wang, 2022), so it is not suitable for large-scale recycling in the future. Upcycling, through a more complex process, can not only recover glass and aluminum frames, but also valuable elements in PV panels, such as silicon and silver, which is a recycling method in urgent need of breakthrough and innovation.

For different components of waste crystalline silicon PV modules, there are different treatment methods, each of which has advantages and disadvantages (Xu, 2018), and there are difficulties in selection. Another factor that has a big impact on the recycling of used PV modules in China is policy. Recycling of PV modules is already mentioned in a number of policy options. For example, the ‘Peak Carbon by 2030 Action Plan’ explicitly proposes to promote recycling of decommissioned PV module waste (The State Council, 2021). The Ministry of Industry and Information Technology and other eight departments jointly issued the ‘Accelerate the implementation plan for the comprehensive utilization of industrial resources’ also proposed to promote the research and development and industrial application of the comprehensive utilization technology related to the waste PV modules, wind power blades and other emerging solid wastes (The State Council, 2022a). However, these policies are not enough to constitute a complete system, and do not involve technical standards and incentive measures related to recycling. As a result, most businesses are still in wait-and-see mode. At present, there are no large enterprises in China that fully focus on PV module recycling. The research and experiment on recycling technology are mostly carried out in some large PV manufacturing enterprises, such as Jinko Solar and Longi (Securities Daily, 2023). This development mode of promoting resource reuse through recycling and remanufacturing conforms to circular economy (Stahel, 2016). It is worth mentioning that small companies with PV module recycling as their sole business have a hard time surviving in China. On the one hand, it is difficult to obtain scrap modules (Xinhua, 2023b). Here, the big PV manufacturers have an inherent advantage. On the other hand, recycling technology is expensive to use, so it is difficult to set a recycling price to obtain stable profits.

Based on the above problems, this thesis aims to explore how to develop competitive PV module recycling technology and enable large-scale diffusion under the current policy background from the perspective of Chinese PV recycling enterprises. The thesis is carried out in two parts: the first part is to build an evaluation system to evaluate different PV module recycling technologies and get the best performance one. The second part is the key part, which aims to establish a Technological Innovation System (TIS) framework based on the innovative recycling technology obtained in the first part. It explores how to scale up the technology from the perspective of Chinese PV module recycling companies (Ortt, 2022). TIS framework is mainly composed of seven building blocks and seven influencing conditions. By collecting available information on the PV module recycling industry in China, each block can be filled and confirmed to be complete, missing, or partially complete. On this basis, considering that the seven influence conditions can affect one or more modules, the reasons for the incompleteness of some blocks can be obtained by evaluating each influencing condition (Ortt, 2022). The incompleteness of these building blocks leads directly to the inability of technologies to proliferate on a large scale. Therefore, some targeted strategies are proposed, including their corresponding background, scale and timing are determined to make up for the incomplete building blocks.

The main structure of this thesis is as follows: Chapter 2 is a literature review of the topics involved, on the basis of which the academic knowledge gap is determined. At the same time, the main research question and six sub-questions are presented, and the research methods for each question are also be introduced. Chapter 3 focuses on the evaluation of different PV module recycling technologies. By setting up an evaluation system, the development priorities of different recycling technologies are determined. In Chapter 4, the TIS framework is used and each building block is filled with specific information. Also, it analyses the seven influencing conditions and obtains the reasons leading to the incomplete building blocks. Chapter 5 explores the strategies that need to be introduced to overcome the incompleteness of building blocks. In Chapter 6, the main research questions and various sub-questions are answered to provide a conclusion. At the same time, limitations, practical implication, scientific implication and further research are also discussed.

2. Literature review and research questions

This chapter aims to identify gaps in academic knowledge through literature review. On this basis, the main research question and sub-questions are proposed, and the research methods for each question are provided.

2.1 Literature review

Due to the multiple academic topics involved, the literature review is carried out in four parts.

2.1.1 Assessment of the PV industry and waste PV modules in China

In order to gain a better understanding of the size of the market for used PV modules in China, it is necessary to fully understand the Chinese PV industry. To this end, some research on the development status of China's PV industry and evaluation of used modules is reviewed in this section.

Wang (2020) used data to show the current situation of China's PV manufacturing, market development, cost reduction and technological innovation. At the same time, the main driving forces for the development of the industry and the prospects for the future of the industry are also analyzed. Yao and Cai (2019) reviewed the development history of PV in China and summarized the different PV technologies. Also, the development status of China's PV industry chain and PV enterprise production is also analyzed.

Wang, et al. (2022) used a three-step approach, i.e., a two-step multiple criteria method (MC) approach to estimate PV deployment downsizing, followed by scenario development, and finally estimated PV waste generation using dynamic material flow analysis (MFA), to evaluate the temporal and spatial characteristics of solar waste in China. Liu, et al. (2022) evaluated the number and geographical distribution of future discarded PV modules in China by establishing a PV retired flow estimation model based on three PV module degradation scenarios. The results show that the accumulated waste is expected to reach 1100~1450 GW by 2060. Similarly, Zhang, et al. (2022) used GM (1,1) model to forecast China's installed PV capacity. At the same time, based on the analysis of multiple factors affecting the failure and life of PV modules, they determined the relevant parameters, and used Weibull distribution model to build a number of scenarios, to predict the future flow of used PV modules in China.

Liu, et al. (2020) evaluated the economic viability of used PV module recycling projects in China by constructing a cost-benefit model. The results show that although these projects are economically feasible, relevant government policies, such as subsidies and tax cuts, can effectively improve enterprise enthusiasm. In addition, the recovery rates and quantities of elements such as silver, aluminum and silicon will have a significant impact on the economics of a recycling project. Song, et al. (2023) developed a dynamic, technology-based material flow analysis model to illuminate the inventory, flow, and secondary supply potential of waste PV panel materials in China from 2000 to 2050. The results show that the polycrystalline glass occupies the largest proportion of the waste, reaching 64%. For precious metal elements, although they account for less than 1% of the total proportion, if they can be recycled, considerable economic benefits can be obtained. Lin, et al. (2022) studied the necessity and feasibility of PV waste recycling in China. The results show that the total recovery method can reduce the environmental burden best. Under current industrial conditions, the net present value of recovery is -1.02$ / kg, making it profitable if silver can be recovered efficiently.

2.1.2 PV module recycling technologies

The research of PV module recycling technology has attracted more and more attention in recent years. These studies focus on the classification of different recycling technologies and explore their advantages and disadvantages. Fthenakis (2000) has long been concerned about the retirement management and recycling of PV modules. He analyzed the feasibility of solar cell recycling in detail and proposed two strategies of centralized and decentralized recycling. From the perspective of closed-loop life cycle, Tao and Yu (2015) studied three recycling ways: manufacturing waste recycling, waste module remanufacturing and recycling. They described the technologies involved and analyzed the pros and cons of each. The results show that although the recycling technology of PV waste and spent modules has been widely explored, the complexity and efficiency of the process still face many challenges. At the same time, although recycling used PV modules has a positive effect on reducing environmental load, it requires policy incentives and the establishment of efficient recycling networks as soon as possible. Lunardi, et al. (2018) listed the different PV recycling technologies being studied around the world, pointing out the advantages and disadvantages of each. Xu, et al. (2018) made a systematic review of the management and recycling technology of waste solar panels. They divided the main methods into three types: component repair, module separation, extraction of silicon and other rare metal elements from components, respectively introducing the principles and advantages and disadvantages of these recycling technologies. Heath, et al. (2020) suggested that the recovery of high-value silicon has advantages over the recovery of intact silicon wafers, so the focus of technology development should be on the purification of silicon. Tao, et al. (2020) considered three recycling scenarios: module reuse, component extraction, and material extraction, and outlined recycling processes in different situations. The results show that module reuse takes the least processing steps and gets the highest benefit, while material extraction is not only complicated, but also has low benefit. The biggest problem for component extraction is the variability of different modules on the market and their cell structures and cell efficiency. Wang, et al. (2022) systematically summarized the end-of-life (EOL) crystalline silicon (c-Si) PV module recycling technology and its condition parameters from three aspects: module disassembly, module layering and material recycling. In addition to discussing the advantages and disadvantages of the current technologies, it is pointed out that these technologies should pay attention to the development direction of high efficiency, economy and environmental protection.

D'Adamo, et al. (2017) proposed a quantitative method to evaluate the profitability of a PV module recycling plant based on a case study of 2000 tons of waste crystalline silicon PV modules. The results show that the recovery of precious metals and materials can have a key impact on economy. Deng, et al. (2019) conducted a techno-economic analysis of recycling technologies for retired silicon PV modules. On the one hand, they divided the recycling methods into downcycling and upcycling, and analyzed the recycling process and principle in detail according to their respective steps. On the other hand, they conducted an economic feasibility analysis of four recycling technologies: landfill, glass recycling, mechanical recycling, and thermal recycling, illustrating their respective advantages and disadvantages. Farrell, et al. (2020) investigated and established the most efficient routes to recycle EOL modules. They reviewed the latest advances in industrial and laboratory-scale recycling methods based on the structure of PV modules, judging whether they can maximize the recovery of components from the modules and help promote a circular economy in the PV industry. The results show that the pyrolysis method provides the best potential for material recovery in c-Si PV modules. Peplow (2022) analyzed the challenges of recycling solar cells. The results showed that the key challenges are untangling the module glass from the solar cell and the disposal of the recovered silicon wafers, both of which require a trade-off between recovery cost and recovery quality.

2.1.3 Circular economy

As the topic of PV recycling receives more and more attention, the circular economy model related to it is also mined. In order to promote a production model based on improving resource efficiency and reducing waste, Sica, et al. (2018) analyzes a clear framework for the management of waste PV panels, highlighting the advantages and disadvantages from the point of view of the transition to circular economy. Mathur, et al. (2020) developed the concept of life cycle symbiosis (LCS) to analyze the recycling of the PV industry. By quantifying the environmental benefits and resource saving benefits of different materials, the most beneficial materials for recycling were obtained. Franco and Groesser (2021) painted a detailed picture of the PV value chain by systematically reviewing the research on the PV value chain (i.e., from product design to product retirement). At the same time, based on the upstream, midstream and downstream stages of the PV value chain, they analyzed the factors that hinder the cycle at each stage and pointed out the corresponding elimination plan. Rabaia, et al. (2022) developed a detailed circular business model for the PV industry, detailing the inputs, outputs, constraints and mechanisms of each stage of the business. The model also identifies environmental, economic, social and technological factors that influence the transition from a traditional one-way business model to a circular and sustainable one.

2.1.4 Technological Innovation System (TIS)

A technological innovation system is a set of elements, including technology, actors, networks and institutions, which, through their interdependent relationships, produce various synergies to promote the development of a specific technology field. Much research has been done on the use and extension of the framework.

Suurs and Hekkert (2009) focused on the functions of a technological innovation system, including entrepreneurial activities, knowledge development, knowledge dissemination, search guidance, market formation, resource mobilization, and support from advocacy coalitions. By analyzing and evaluating the development of biofuels in the Netherlands, they illustrated how these system functions are established over time, and the impact of dynamics on the system. Bergek, et al. (2015) believed that the dynamics of technological innovation systems are affected by various contextual structures. After conceptualizing this context in detail, they analyzed their influence on technological developments.

Ortt and Kamp (2022) conceptualized a technology innovation system framework for developing and researching niche introduction strategies from a company perspective. This is also the analytical framework used in this thesis, and the main structure is shown in Figure 1. The framework consists of seven TIS building blocks and seven conditions that affect these building blocks, they are described as follows:

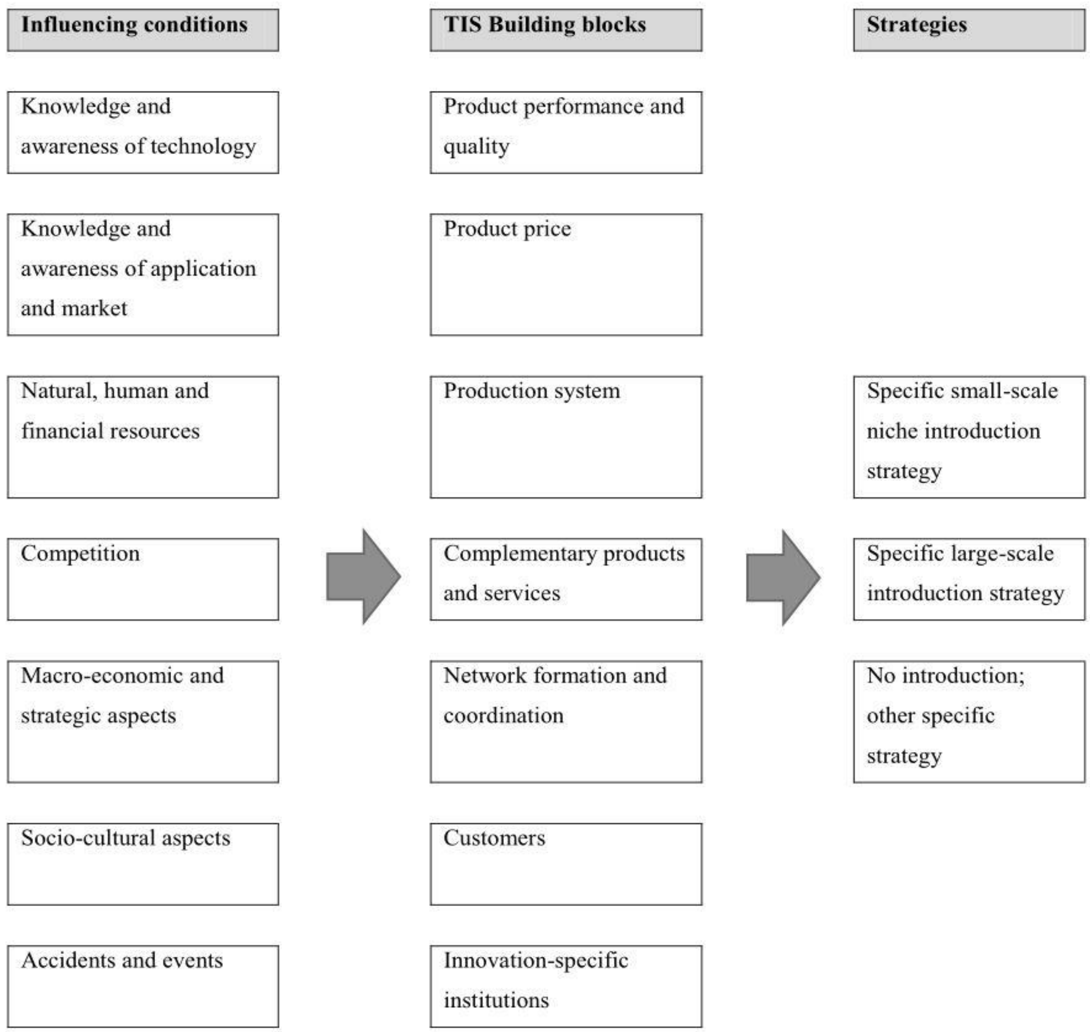

Figure 1: Technological Innovation System (TIS) Framework (Ortt, 2022)

Building blocks:

Product performance and quality: Compared with competitive products, high-tech products need to have sufficient performance and quality now or in the future. These products must meet the needs of the target customer so that they see the product as a viable option (Ortt, 2022).

Product price: It includes the financial and non-financial costs of obtaining and using the product. These costs include: time and effort costs, investment-related costs, switching costs, and transaction costs. In order for the product to proliferate on a large scale, a reasonable price is indispensable (Ortt, 2022).

Production system: In order to achieve large-scale diffusion, the production system is indispensable. It is capable of mass production and delivery of products with guaranteed quality (Ortt, 2022).

Complementary products and service: The availability of complementary products and services that support the development, production, distribution, use, repair, maintenance and disposal of innovative technologies plays a positive role in the large-scale diffusion (Ortt, 2022).

Network formation and coordination: This building block focuses on actors in the supply chain. Multiple types of actors, including component suppliers, actors who assemble products, distributors, and actors who provide complementary products, play an important role in the large-scale diffusion of innovation. There is a need for coordination among these actors to develop practical cooperation or to jointly promote the vision of technological innovation (Ortt, 2022).

Customers: In order to achieve large-scale diffusion, customers should be segmented as early as possible to identify potential customers who have a demand for innovation. To turn them into real customers, they need to know the product well enough to see its advantages, and have the knowledge, means, and willingness to acquire and use it (Ortt, 2022).

Innovation-specific institutions: Institutions refer to formal laws, policies, and regulations that either describe the norms and requirements for products, production facilities, and complementary products and services, or describe how market participants should handle products and the systems around them. Achieving large-scale diffusion requires specific institutions (Ortt, 2022).

Influencing conditions:

Knowledge and awareness of technology: The knowledge here includes fundamental and applied knowledge. Fundamental knowledge refers to the technical principles related to the components of TIS (including products, production systems, complementary products and services). Applied knowledge refers to the knowledge required to develop, produce, repair, maintain and improve these TIS components (Ortt, 2022).

Knowledge and awareness of application and market: This influencing condition refers to how and in which applications the innovation is used. In addition, it also includes an understanding of the market structure and relevant participants. This knowledge can be gained through market analysis, experimentation, practice, or interaction with relevant actors (Ortt, 2022).

Natural, human and financial resources: This influencing condition refers to the availability of the resource. There are three types of resources: first, the natural resources needed to create products, production systems and complementary products. Second, human resources with appropriate knowledge and capacity need to be mobilized. The third is the financial resources required for the development and application of innovations, production systems and complementary products, which can come from different types of participants (Ortt, 2022).

Competition: In this influencing condition, competition on the one hand refers to the competition between products based on old and new technologies. On the other hand, there is also competition between different product versions with new technologies. Complex competitive patterns may hinder the formation of TIS building blocks (Ortt, 2022).

Macro-economic and strategic aspects: Macro-economic growth and recession may promote and hinder the formation of TIS building blocks. The economic situation involves conditions such as market structure and contemporary ways of doing business, which are often reflected in the state's strategies on important industries. The combination of the above conditions will have an impact on the formation of TIS building blocks (Ortt, 2022).

Socio-cultural aspects: This influencing condition refers to the norms and values held by potential customers and other important actors in the socio-technical system. These aspects are less formal than institutions, but can have a significant impact on the formation of institutions and the behavior of actors. In addition, socio-cultural aspects change over time (Ortt, 2022).

Accidents and events: On the one hand, accidents refer to accidents within TIS, such as production accidents and failure accidents. On the other hand, it also refers to accidents other than TIS, such as wars and natural disasters. This influencing condition can have an impact on the formation of multiple TIS building blocks (Ortt, 2022).

When using the framework, the main process is as follows: The first step is to gather information and populate the seven building blocks. On this basis, confirm whether each module is complete, missing or partially complete. The second step focuses on the seven impact factors. Since each of them can have an impact on one or more building blocks, analyzing them can lead to the reasons for the missing or incomplete building blocks. The third step is on the basis of the second step, according to the obtained reasons, to determine the strategies to be introduced. Information about these strategies, including the timing, size, and type of introduction, should be detailed.

2.2 Academic knowledge gap

According to the above literature review, it can be found that there are academic knowledge gaps in the following aspects. First, most of the research on silicon PV module recycling technologies is to introduce their principles, analyze their advantages and disadvantages, and rarely compare them according to certain established standards. Although some studies have compared several recycling technologies at the economic level, it is not enough to focus only on the economy of the technology. In fact, the environmental impact of PV module recycling technology cannot be ignored. Different technologies have different degrees of impact. In addition, considering the development of PV in China, the applicability of recycling technology to PV power plants in different regions and of different scales is also an issue to be considered.

Second, regarding the use of TIS framework, most studies use is to analyze past cases in which technologies have matured over time. However, for the majority of waste PV module recycling technologies, they are only developed at the enterprise trial or experimental research stage. It is necessary to construct a new technological innovation system for them.

Third, it is difficult to find literature related to China's PV module recycling industry at this stage. This is mainly reflected in three aspects: First, there is a lack of literature analyzing the current situation of China's PV module recycling industry. Second, there is a lack of convincing research to show the barriers to large-scale development of the industry in China. Third, there is no analysis of the literature of the various participants in China's PV module recycling industry, resulting in a state of uncertainty as to what actions these participants should take next.

2.3 Main research question and sub-questions

Based on the above academic knowledge gap, the research objectives of this thesis are determined. First, from the economic, environmental protection, applicability and some other social aspects, establish a set of evaluation criteria. A variety of waste PV module recycling technologies with development potential were selected for comparison, and the most suitable recycling technology for large-scale use in China in the future will be obtained based on this standard. Secondly, to construct a TIS framework for this recycling technology, mainly from the perspective of Chinese PV module recycling enterprises, to analyze what niche strategies should be adopted to promote its large-scale diffusion. With the above research objectives, the main research question of this thesis is thus obtained:

'How can Chinese PV module recycling companies scale up a new recycling technology?'

In order to facilitate detailed and in-depth research, the main research question is divided into the following six sub-questions:

1. Which waste silicon PV module recycling technologies have the development prospect in China?
2. How to develop a set of criteria for assessing their strengths and weaknesses?
3. How well do these technologies perform against this set of criteria, and which one is best?
4. How well is the Technological Innovation System for waste crystalline silicon PV module recycling technology developed in China?
5. What is influencing the current development of the Technological Innovation System for waste crystalline silicon PV module recycling technology in China?
6. What strategies could be adopted to enable large scale diffusion of waste silicon PV module recycling technologies in China?

2.4 Methodology

This section follows the order of the sub questions to explain which research methods should be used to obtain the respective answers. In addition, research design and research procedures are also discussed.

2.4.1 Research methods to each sub-question:

1. 'Which waste silicon PV module recycling technologies have the development prospect in China?'

In order to obtain a promising technology for recycling waste silicon PV modules, a full literature review was carried out first. As mentioned in section 2.1, the research work done by Xu, et al. (2018) and Wang, et al. (2022) all systematically classified and introduced the principles of crystalline silicon PV module recycling technology. These references were important sources for obtaining advanced recycling technology. In addition to the retrospective literature, some studies on the recycling technology of a particular material were also noteworthy, such as Kang's (2012) study on the process of recycling silicon and glass. After having a full understanding of the principle, advantages and disadvantages of recycling technology, it was possible to select several typical technologies with rich development potential.

In addition, qualitative analysis was used in the selection of recovery technology. Although the methods involved in downcycling, such as landfill, are simple to operate, but the economy is very poor, and environmental factors are ignored to some extent, so they are not suitable for large-scale diffusion in the future. The technology involved in upcycling was the focus of this thesis. In terms of recycling, these technologies could be roughly divided into two categories. One is the dismantling and layering of modules. The second is the separation and recovery of valuable elements (Wang, 2022). There are many module delamination methods, such as thermal delamination, mechanical delamination, chemical delamination, etc. Due to the wide variety of technologies, taken together, an initial qualitative comparison was used to pick out the technologies that have potential for development in the first impression.

2. ‘How to develop a set of criteria for assessing their strengths and weaknesses?’

To solve this sub-problem, the preliminary research methods were as follows: The evaluation criteria of recycling technology were divided into five aspects: economy, environmental protection, applicability, technical effectiveness and social factors. The assessment of the economics of recycling technologies was based on an estimate of the costs of these technologies and an estimate of the value of the recycled materials obtained. Crystalline silicon solar panels involve many materials, and their weight percentages vary greatly. At the same time, there is a big difference in the market price of these materials once they are recycled. Therefore, the evaluation of the value of recycled materials was combined with its price and weight factors. Similarly, estimates of the cost of recovery technologies were focus on the cost of the instruments and reagents used in these technologies. Finally, the economy of recycling technology was evaluated by integrating the cost of technology implementation and the value of recycled materials. The evaluation of economy mainly involved quantitative analysis.

A similar approach was adopted for environmental assessment. The main embodiment was to fully consider the impact of pollutants produced in the recycling process of different technologies on the environment. It is worth mentioning that the analysis of environmental impact here was qualitative, because it was difficult to quantify the impact of the products in the recycling process on the environment. For example, in order to extract metal materials and silicon elements, the use of reagents to infiltrate the material, will produce nitric acid wastewater; When thermal delamination is used, toxic gases such as nitrides are produced. It is difficult to quantify the environmental impact of either product, but it is clear that toxic gases are more harmful to the environment.

Similarly, the applicability of various recycling technologies in China was also qualitatively analyzed. According to the development of PV in China, large-scale PV power stations rather than distributed PV were developed first. Therefore, the recycling technologies suitable for mass processing of waste modules, or the recycling process was relatively simple, have certain advantages in applicability. In addition, regional differences in PV development in China also affected the applicability of recycling technology. For example, western China is often the site for the construction of large-scale PV power stations due to sufficient lighting resources, but the economy is more backward than that of eastern China, and the environment is less friendly. Whether recycling technologies are suitable for these areas was also an issue that needs to be considered.

The effectiveness, or reliability, of different technologies was another criterion that needed to be evaluated quantitatively. For example, separation rate was a key parameter for module delamination. For the recovery of valuable metals, the recovery rate of each metal element was also an important reference to evaluate the excellence of different technologies.

The last criteria were other social factors. For example, the public's acceptance of certain recycling technologies. Most of the recycling methods used in the recovery of various metals in PV modules produce waste. If the waste has an impact on public life, it would inevitably lead to resistance and thus reduce the competitiveness of recycling technology. In addition, whether certain recycling technologies have been put into use in PV recycling enterprises in China was also considered as a part of the evaluation criteria of social factors, because if they have been put into use in practice, it indicates certain experience and its outstanding advantages.

It should be noted that these evaluation criteria were determined based on existing literature and reports. The study evaluated different aspects of recycling technology from as comprehensive a perspective as possible by reading literature and reports on Chinese PV modules.

3. ***'How well do these technologies perform against this set of criteria, and which one is best?'***

With the above foundation, that was, constructing a complete set of evaluation criteria, this sub question can be answered. Firstly, based on the literature and reports, different selected PV module recycling technologies were evaluated under different criteria and their respective evaluation results were obtained. The results of these assessments were divided into different grades, and each grade corresponded to a different score. For example, best and worst were two evaluation levels, which corresponded to a score of 5 and 1 respectively. At the same time, the weight of each criterion was determined based on the literature and the actual situation. In this way, the final step of the evaluation became quantitative analysis. For each recycling technology, its score could be calculated, that is, the weight of each criterion was multiplied with the corresponding evaluation score to obtain a weighted score under each criterion, and the weighted scores of all criteria were added together to give the final score of the technology.

4. ***'How well is the Technological Innovation System for waste crystalline silicon PV module recycling technology developed in China?'***

This sub-problem can be solved after constructing a TIS framework. The method was based on the work of Ortt and Kamp (2022), whose framework innovatively evaluates when and how to introduce strategies for specific niches from a firm perspective. This was in line with part of the research objective of this thesis, which was to analyze how to spread emerging PV module recycling technologies on a large scale. The framework consists of seven TIS building blocks and seven corresponding influencing conditions. In this sub-question, the main objective was to evaluate the various building blocks of TIS. The research method adopted was to extract information that can fill in the building blocks through desk research, including reading relevant reports and news. At the same time, by arranging an interview with a participant (Engaged in the testing of PV modules and PV systems) in the PV module industry in China, the author was able to get the most up-to-date information from him about the industry and his views on PV module recycling. Combined with the information collected above, the information filling and status judgment of TIS building module were completed. It should be pointed out that an objective attitude was held when judging the status of TIS building blocks, and no matter what assessment judgment was made, it needed to be based on evidence. In addition, considering that there was little literature related to PV module recycling in China, the cited sources of the desk research were mainly the official websites of different PV module recycling companies, as well as some news websites that report on module recycling. Their persuasiveness and reliability may not match that of the literature. However, reliable news or reporting sources were used as much as possible during the research process.

5. ***'What is influencing the current development of the Technological Innovation System for waste crystalline silicon PV module recycling technology in China?'***

After evaluating the status of TIS building blocks, the core of this sub-question was to evaluate the various influencing conditions. Similar to the research method of the above sub-question, desk research was used to gather the information needed to assess the state of the influencing conditions. In addition, an interview with the practitioner (Engaged in the testing of PV modules and PV systems) was also a source of information. Through the combination of the two, the qualitative analysis had a basis. In addition to making judgments about the state of the influencing conditions, the results of the analysis also included which building blocks they affected and how they brought those building blocks to their current state. After this sub-question was solved, the cause of partial or incomplete building blocks was identified, and the corresponding obstacles to the large-scale diffusion of China's PV module recycling were listed.

6. ***'What strategies could be adopted to enable large scale diffusion of waste silicon PV module recycling technologies in China?'***

After getting the causes of missing or incomplete blocks, this sub-question focused on the timing, scale, and specifics of the introduction of the appropriate niche strategies to address the missing or incomplete or existing barriers to the TIS building blocks. The research methods used were as follows: First, through literature review, the types, contents and usage scenarios of niche strategies were fully understood. Then the qualitative analysis was carried out, based on the current barriers to the large-scale diffusion of PV module recycling in China, and the corresponding niche strategies were formulated from the perspective of enterprises. These niche strategies could be of the type identified in the literature, or they could be other strategies that were effective in removing barriers. The specific scale, introduction time and specific content of these strategies needed to be determined through desk research combined with the actual situation in China.

2.4.2 Research design and research procedures

This study aims to understand the different PV module recycling technologies and explore how to make them diffuse on a large scale in China. In this case, the research context was undoubtedly set in China. The data collected was primarily qualitative. When evaluating various module recycling technologies, the data was derived from the specific scientific literature, which was either the latest development of the specific technology or a summary of all mainstream PV module recycling technologies. When the TIS framework was used for analysis, the data collected was mainly from desk research, including: the website of PV module recycling companies, news and reports on major seminars and academic conferences held within the industry, newspapers and websites that regularly report on the PV module recycling industry, and official pages that publish relevant policies and standards. Since there was very little literature available on this subject, information was collected mainly through desk research. In addition, the only interview with Chinese PV industry practitioner was also an important source of information.

The steps of the research were carried out in the order of each sub-question. Among them, the first three sub-questions constituted the first part of the research, while the last three sub-questions constituted the second part of the research. It should be noted that the first and second sub-questions were independent of each other, but the third sub-question was built on the solutions of the first two. Therefore, the technologies selected in the first sub-question and the evaluation system built in the second sub-question were fed into the third sub-question. Only when the two were combined can the final evaluation result be obtained. For the second part of the study, after the fourth sub-question was answered, its answer, i.e., the status of each building block, was entered into the fifth sub-question. In conjunction with these answers, an assessment of the various influencing conditions was completed and their connection to the building blocks was also discussed. The last sub-question built on the answers to the fourth and fifth sub-questions. An assessment of the building blocks and influencing conditions revealed the obstacles that hinder the large-scale diffusion of PV module recycling in China. Specific information about these barriers was fed into the sixth sub-question, on which corresponding solution strategies were developed to remove the barriers. In general, the research followed a strict step sequence to complete the answers to each sub-question.

3. Evaluation of different PV recycling technologies

The purpose of this chapter is to evaluate the different recycling technologies of crystalline silicon (c-Si) PV modules. The specific structure is as follows: Section 3.1 briefly introduces the typical structure of c-Si PV modules, and lists the detailed components. Section 3.2 selects several typical recycling technologies and introduces their principles briefly. Section 3.3 sets up an evaluation system for recycling technologies. In Section 3.4, the different technologies selected are put into the system for evaluation. Section 3.5 provides a brief discussion of the evaluation results in Section 3.4. It is worth mentioning that sections 3.1 and 3.2 are responses to sub-question 1: ***Which waste silicon PV module recycling technologies have the development prospect in China?*** Section 3.3 is a response to sub-question 2: ***How to develop a set of criteria for assessing their strengths and weaknesses?*** Sections 3.4 and 3.5 are responses to sub-question 3: ***How well do these technologies perform against this set of criteria, and which one is best?***

3.1 Typical structure of a c-Si PV panel

As a PV panel with early development and mature technology, c-Si PV panel occupies more than 90% of the market share. Therefore, when the tide of PV module retirement comes, c-Si PV panels will act as the leading force (Wang, 2022). The structure of c-Si PV panel is shown in Figure 2.

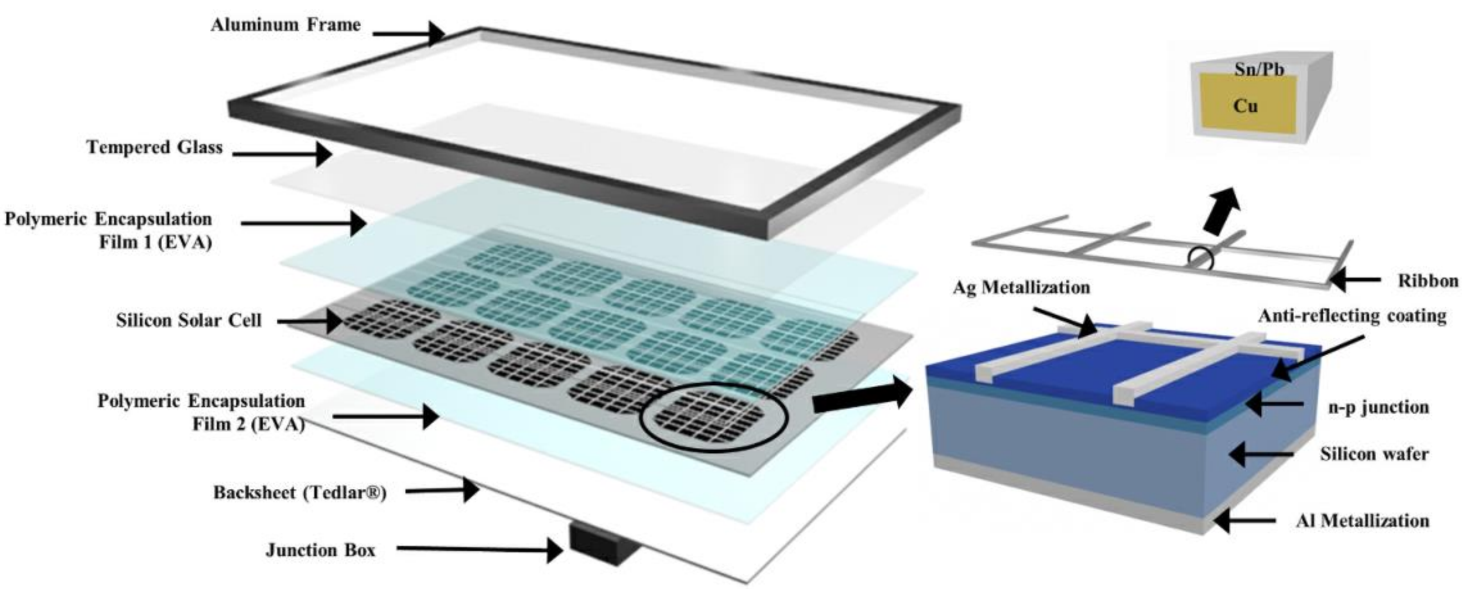

Figure 2: Structure diagram of a c-Si PV panel (Wang, 2022)

The components are different for different locations of the structure. The main component of the frame is aluminum, while the main substance of the polymeric encapsulation (EVA) layer is polymer, which has no recovery value. Also of no recycling value is the back sheet, which is made of organic materials. For the solar cell layer, its structure contains silicon, silver, copper and some other metal elements, so there is a greater recovery value. Table 1 lists the materials that make up c-Si solar modules and their respective proportions.

Table 1: The materials of a PV module and their proportion (Wang, 2022)

Material	**Weight percentage (%)**
Silicon	2–3
Silver	0.006 ~ 0.08
Copper	4.4–7
Aluminum	10 ~ 20
Glass	69 ~ 75
Junction box	2
EVA	7
Boron	< 0.1
Phosphorus	< 0.1
Tin Dioxide	< 0.1
Lead	< 0.1

It can be seen that the largest proportion of PV modules is glass, reaching nearly three quarters of the total mass. For some metallic elements, such as boron, phosphorus, and lead, they make up too low a percentage of components to be recycled. The real focus is on silicon, as well as metal elements such as silver, copper and aluminum.

3.2 Several typical recycling techniques

Typically, PV modules are recycled by disassembly as a pre-treatment, i.e., manually or mechanically removing junction boxes and cables (Wang, 2022). The frame can be recovered by secondary metallurgy (Jung, 2016). The remaining ‘glass-EVA-solar cell-EVA-back sheet’ structure requires further processing techniques. The processing technologies associated with this section can be divided into three categories: downcycling, recycling, and upcycling, as shown in Figure 3.

Downcycling and cycling are relatively simple recycling methods, often in the form of mechanical separation, incineration and landfill. Despite the low input cost of these technologies, the quality of the materials recovered cannot be guaranteed (Wang, 2022). Therefore, they are not suitable for future large-scale diffusion. The recycling technology mainly concerned in this thesis is upcycling.

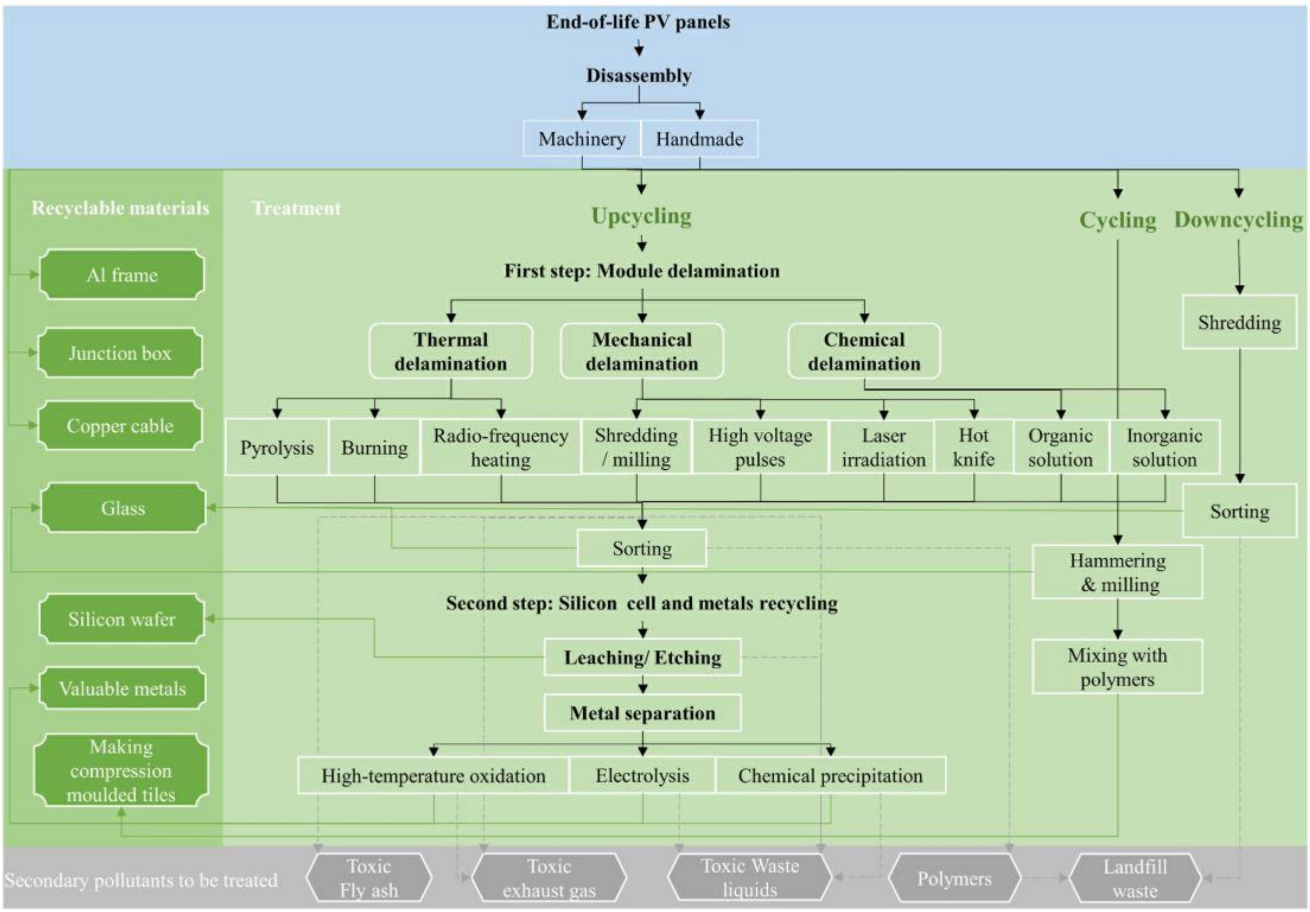

Figure 3: Recycling technologies of c-Si PV modules (Wang, 2022)

Upcycling consists of two steps: module delamination and solar cell recycling (Deng, 2019). Since there is a clear sequence of steps, defining the PV module recycling method cannot be limited to one technology. In other words, a recycling method is a combination of two or more technologies and exists in chronological order when it is actually used. As can be seen from Figure 3, a complete upcycling method can be formed by combining one of the technologies in module layering in step 1 with one of the technologies in solar cell recycling in step 2. Module delamination can be achieved in three ways: thermal, mechanical and chemical delamination. In this step, the key point is whether the EVA layer can be effectively removed. Although the above three processing methods differ in principle, the main purpose is to achieve the separation of the EVA layer from the solar cell layer and the glass layer, so as to facilitate the next processing. Figure 3 also shows that for each module delamination technique, there are multiple implementations. For example, chemical delamination can be achieved by adding organic and inorganic reagents. It should be noted that the research focus of this thesis is not at the technical level, so for each module delamination technology, only one representative method is selected to enter into the subsequent analysis, rather than a detailed comparison of all methods. The same is true for the second step. The recycling of solar cells includes the recycling of silicon wafers, and the recycling of valuable metals. As for the recycling technology of silicon wafers, chemical etching is often used as a method. The recovery technology of valuable metals can be divided into three methods: wet metallurgy, electrochemical assisted leaching and wire explosion (High-voltage pulsed discharge). Based on the above, typical upcycling technology combinations are obtained.

Table 2: Selected typical upcycling technologies

<table>
<tr><th colspan="2">Steps</th><th>Technologies</th><th>Methods</th></tr>
<tr><td colspan="2" rowspan="3">Step 1: module delamination</td><td>Thermal delamination</td><td>Two-stage pyrolysis</td></tr>
<tr><td>Mechanical delamination</td><td>High-voltage pulse</td></tr>
<tr><td>Chemical delamination</td><td>Organic reagents</td></tr>
<tr><td rowspan="4">Step 2: solar cell recycling</td><td>The recycling of silicon wafers</td><td>Chemical etching</td><td></td></tr>
<tr><td rowspan="3">The recycling of valuable metals</td><td>Wet metallurgy</td><td rowspan="3"></td></tr>
<tr><td>Electrochemical assisted leaching</td></tr>
<tr><td>Wire explosion (High-voltage pulsed discharge)</td></tr>
</table>

Table 2 shows a selection of typical upcycling technologies that will be evaluated in the evaluation system to come up with a best-performing combination of technologies.

3.3 The establishment of evaluation system

After selecting several PV module recycling technologies to be evaluated, the evaluation system is set up in this section. For technology evaluation, both single- and multi-criteria analysis methods can be used (Billig, 2017). This thesis will use a multi-criteria assessment. To do this, two questions need to be considered:

1. What evaluation criteria constitute the whole system?

2. What are the reasons for choosing these evaluation criteria?

For waste PV module recycling enterprises, it is important to ensure profitability (D’Adamo, 2017). Therefore, the economy of the recycling technology used is a criterion worth evaluating. For a solar system, although clean to operate, the manufacturing process comes with a huge environmental burden (Huang, 2017). As a part of the manufacturing process, it is necessary to consider the environmental impact of PV module recycling. Therefore, environmental protection will also be a criterion in the evaluation system. In addition, China's centralized PV power stations developed earlier, but there is serious light abandonment phenomenon. Distributed photovoltaics have grown rapidly in recent years (Xin-gang, 2019). Therefore, there are different types and scales of PV power generation, and the applicability of recycling technology to them also needs to be considered. Similarly, the applicability of different recycling technologies to different regions varies. Northwestern China, such as Xinjiang, Inner Mongolia, Qinghai and Gansu provinces, has high solar irradiance throughout the year and are suitable for the development of centralized PV (Liu, 2019). However, these areas are far inland and remote, making it difficult to dispose of discarded modules in large quantities and transport them. While provinces such as Shandong, Jiangsu and Guangdong, despite moderate solar irradiance, have seen rapid growth in installed capacity of distributed PV due to rapid economic development and high demand for electricity (Liu, 2019). Disposal of waste modules in these areas, although convenient transportation, but widely distributed. Therefore, the applicability of different recycling technologies varies greatly in different regions. All of these things will be evaluated under the 'applicability' criteria. Looking back at the recycling technologies themselves, it is also worth evaluating their reliability, or rather their effectiveness. In the first step of PV module recycling, module separation, the reliability of the technology is reflected in the separation rate. In the second step, the recovery of valuable metals, the effectiveness of different technologies is reflected in the recovery rate of metals. The last criterion can be other social factors. On the one hand, it takes into account the acceptability of different recycling technologies in the minds of the general public, and generally safety plays a decisive role. On the other hand, it also considers the current practical application of different recycling technologies. The above discussion is the answer to the two questions posed at the beginning of this section. What follows is a detailed look at each of the criteria.

3.3.1 Economy

In this criterion, the economic status of different recycling technologies will be compared and analyzed. A combination of quantitative and qualitative analysis is used in this process. First, for different PV module recycling technologies, the cost of processing the modules is a key component of the economics of the technology. The further subdivision of the recovery cost, the instruments and reagents used in the treatment (Cui, 2022), as well as the complexity of the treatment process, all have an impact on the cost. On the other hand, the value of the materials obtained at each stage of recycling is also part of the economics of recycling technology. Although quantitative analysis is more intuitive and convincing in the evaluation of economy, it is difficult to obtain accurate figure of other data, such as the cost of instruments and reagents used in the recovery process, except the recovered materials which can be directly estimated quantitatively. This is partly because many advanced recycling techniques are being tested in the laboratory (Wang, 2022), and detailed processing costs are not available directly from the literature. The complexity of recycling, on the other hand, is hard to quantify. Therefore, the combination of quantitative and qualitative analysis is the most suitable way to evaluate the criterion of economy.

3.3.2 Environmental protection

As mentioned earlier, PV module upcycling can be divided into two steps, module delamination and solar cell recycling. However, most recycling processes produce waste that is harmful to the environment. As mentioned earlier, PV module upcycling can be divided into two steps, module delamination and solar cell recycling. However, most recycling processes produce waste that is harmful to the environment. For example, when thermal delamination is performed using high-temperature pyrolysis, the back sheet will decompose at high temperatures into harmful fluorinated by-products (Hagiwara, 1977). When using hydrometallurgy to recover valuable metals, if using nitric acid solution to leach anions, in the process of use will produce waste acid solution and toxic fumes, which will be harmful to the environment. When hydrometallurgy is used to recover valuable metals, if silver ions are leached with nitric acid solution, waste acid solution and toxic smoke will be produced in the process of use (Yang, 2017), which is harmful to the environment. Therefore, it is worth evaluating whether different recycling technologies will have an impact on the environment during their implementation. The qualitative method is adopted for environmental protection assessment. This is because it is difficult to quantify the environmental impact of hazardous materials produced in the recycling process, so the environmental friendliness of different products can only be evaluated by comparing their harmful degree and the ease of disposal.

3.3.3 Applicability

Qualitative analysis will be used to evaluate the applicability. This assessment criteria can be further divided into two parts: one is whether the recycling technology being assessed is suitable for use in remote areas, and the other is whether the recycling technology being assessed is suitable for large-scale processing. As mentioned earlier, the northwestern provinces of China, including Xinjiang, Inner Mongolia, Qinghai and Gansu, have become the provinces with the largest number of centralized PV systems installed thanks to high irradiance throughout the year (Liu, 2019). Although distributed PV has grown rapidly in Shandong, Jiangsu, Zhejiang and Guangdong provinces in recent years, centralized PV plants will experience the peak of module recycling first, considering the average lifespan of PV modules. Therefore, this thesis will mainly consider the recovery of modules in centralized PV power stations. Given the relative remoteness and inaccessibility of northwest China, transporting the discarded modules can be a big problem. Therefore, for different recycling technologies, whether they are suitable for use nearby is very important. That is, whether the technologies being evaluated are suitable for setting up recycling sites around large centralized PV power stations to complete the recycling process. Another important component of applicability is whether the recycling technology being evaluated is suitable for large-scale use. In the case of centralized PV plants, once the modules are decommissioned, the number is bound to be huge. Therefore, technologies suitable for processing modules at scale will have an advantage.

3.3.4 Technical effectiveness

In this evaluation criterion, the effectiveness of recycling technologies themselves will be quantitatively compared and analyzed. For different steps in the recovery process, the core parameters to evaluate the technical effectiveness are also different. In the first step, module delamination, the evaluation needs to focus on the separation rate, that is, how effectively the EVA layer separates from the solar cell layer. In the second step, solar cell recycling, the evaluation needs to focus on the recovery rate of valuable metals. These metals mainly include silver, aluminum, copper and so on. Since silver has the highest value among all metals, its recovery rate will greatly affect the effectiveness of the second recovery step.

3.3.5 Other social factors

Qualitative methods will be used to evaluate this criterion. It is further refined into two parts. The first part is whether the recycling technology being evaluated is acceptable to the public. Obviously, whether the technology itself is safe and whether the waste produced after use will have an impact on people's daily life are the main standards. The second part is to evaluate the current application of PV module recycling technology. For example, if a company is already using a recycling technology on a scale, that technology has a definite advantage over something that is still being researched and tested in the lab.

It should be pointed out that the above five criteria have different weights in the total score, and their importance cannot be simply divided equally. For a PV module recycling technology to develop in China, the effectiveness of the technology itself should be high, and the technology must be suitable for batch processing. Therefore, the two criteria of applicability and technical effectiveness should occupy the highest weight in the total score, which is set at 25% in this study. Economy is less important than the above two criteria, but it still plays an important role in the process of large-scale diffusion of technology, so its proportion of the total score is set at 20%. The remaining two criteria, environmental friendliness and other social factors, do not play a decisive role, so they are given the lowest weight in the overall score, both 15%. It is worth noting that the setting of the weights of each of the above criteria is subjective, which will be explained in the last chapter of the thesis.

3.4 Evaluation of various recycling technologies

This section evaluates the different PV module recycling technologies. As described in Section 3.2, PV module upcycling is divided into two steps: module delamination and solar cell recycling. Various recycling techniques are involved in each step. Therefore, the evaluation methods are as follows: ① The evaluation system established in Section 3.3 is used to evaluate the five criteria separately. ② Distinguish the two processing steps. The three typical processing technologies selected in the first step (namely two-stage pyrolysis, high-voltage pulse, and organic reagents) and the three processing technologies selected in the second step (namely wet metallurgy, electrochemical assisted leaching and wire explosion (High-voltage pulsed discharge)) are evaluated respectively. After obtaining the best processing technology in each step, the combination of the two is the best upcycling processing mode. It is worth mentioning that in the second step, solar cell recycling, chemical etching method is a relatively unified recycling method for silicon wafers, so it is not put into the evaluation system. Therefore, the recycling techniques mentioned above in the second step are all aimed at recovering valuable metals. For each technology, performance under each criterion is represented by the following relative scale, as shown in table 3. In addition, for each symbol, its representative score is different. From the sign '⊕' in the first row to the sign '⊖' in the last row in table 3, the score represented decreases from 5 to 1. Tables 4 and 6 show the technologies to be evaluated in step 1 and step 2, respectively.

Table 3: The relative scale used in the evaluation

Symbol	**Meaning**	**Representative score**
⊕	The best	5
+	Better than average	4
0	Average	3
−	Worse than average	2
⊖	The worst	1

3.4.1 Step 1: Module delamination

Table 4: Recovery techniques to be evaluated in Step 1

Technologies	**Methods**
Thermal delamination	Two-stage pyrolysis
Mechanical delamination	High-voltage pulse
Chemical delamination	Organic reagents

(1) Economy

For thermal delamination, the back sheet should be effectively removed by milling first to reduce the harmful products produced during the pyrolysis process (Fiandra, 2019). The treatment is then carried out at 500°C for one hour with the thermal treatment unit shown in Figure 4.

From the perspective of recovery cost, on the one hand, the whole treatment process is relatively complex, requiring mechanical pretreatment and thermal treatment, and the experience time is relatively long. Processing, on the other hand, involves the milling machine and the various instruments that make up the thermal treatment unit, and although they can be used repeatedly, the overall cost of equipment is high. From the perspective of recovery income, the two-stage pyrolysis method effectively removes the EVA layer, and about 90% of the total mass of PV panel can be recovered (Fiandra, 2019), so the return is relatively high. Based on the above analysis, the evaluation result of thermal delamination technology of two-stage pyrolysis under the criterion of economy is '-', that is, worse than the average level.

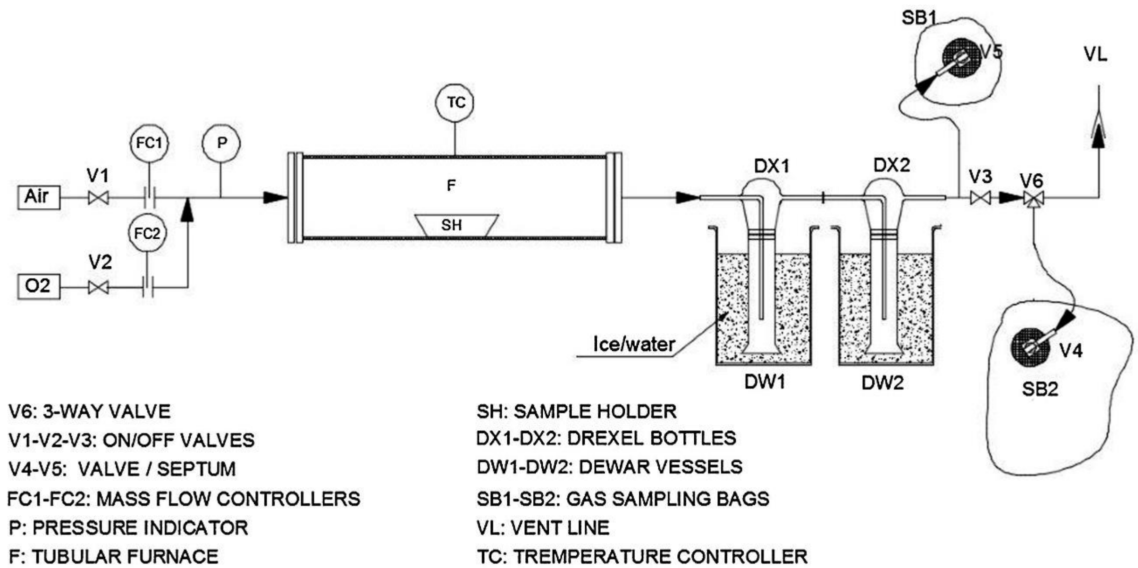

Figure 4: Thermal treatment experimental facility (Fiandra, 2019)

For mechanical delamination, high voltage pulse recovery treatment, through the method of two crushing and physical separation, can effectively complete the collection of PV module materials. The estimated processing cost of this process is \$0.0019/W (Akimoto, 2018), which is much lower than the installation and use costs of PV modules. Although the recycling process is not simple, requiring two crushing, separation and collection, its highly competitive recycling costs indicate its commercial potential. In terms of recovery benefits, this treatment effectively separates the glass and metal from modules. If silver is further condensed, the concentration of silver in the heavy product will be more than 30 times higher than before (Akimoto, 2018), which has a very considerable recovery benefit. Based on the above analysis, the evaluation result of mechanical delamination technology of high voltage pulse is '+' under the criterion of economy, that is, better than the average level.

For chemical delamination, the organic reagent trichloroethylene (TCE) is used to separate the EVA layer from the solar cell layer. Considering the long separation time of PV panels using traditional chemical methods, Pang et al. (2021) can achieve efficient separation by using the new technology of microwave enhanced swelling of EVA films. In this case, it takes only two hours to completely separate the PV panels. In this treatment, the recovery cost is not high. On the one hand, the price of the organic reagent TCE used is not high, about $10/ton (Chemical Book, 2023). On the other hand, the microwave processing device used (as shown in Figure 5) is also relatively simple. In general, the technology is inexpensive. In addition, the returns are high. The PV panel can be completely separated in a short time, which is convenient for recycling and material extraction of solar cells in the second step. In general, the delamination of modules using organic reagents is economically viable. Based on the above analysis, the evaluation result of chemical delamination technology using organic reagents under the criterion of economy is ‘0’, that is, equal to the average level.

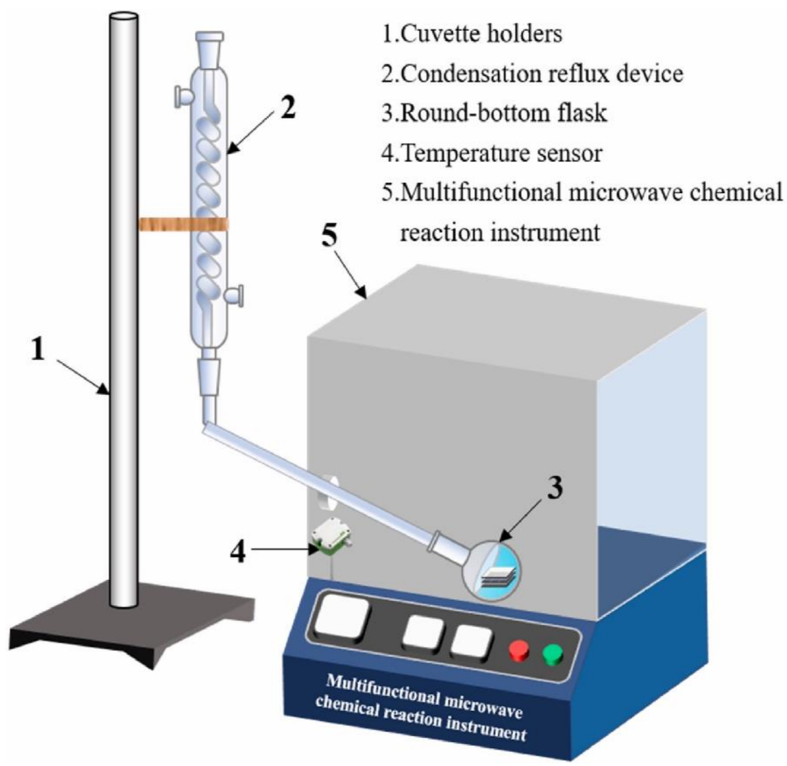

Figure 5: Microwave processing equipment (Pang, 2021)

(2) Environmental protection

For the two-stage pyrolysis recovery method, milling the back sheet in the first stage does not cause any environmental harm. In the second stage of high temperature pyrolysis, EVA layer will produce a large number of volatile organic compounds (Fiandra, 2019).

Although gas sampling bags have been set up in the device in Figure 4 to collect by-products, how to deal with these substances harmful to the environment afterwards is still a problem to be considered. In summary, the evaluation result of the recovery method of two-stage pyrolysis under the criterion of environmental protection is ‘0’, that is, equal to the average level.

As for the recycling method of high voltage pulse, the whole process only involves mechanical treatment, so no harmful pollutant is produced. In general, the recovery method of high voltage pulse is evaluated as ‘⊕’ under the criterion of environmental protection, that is, the best level.

For chemical delamination using organic reagents, the TCE reagent used is carcinogenic (Slunge, 2022). Therefore, whether in the process of industrial recovery, or after the recovery of the reagent, operators need to pay special attention to its harm. Overall, the chemical delamination method using organic reagents is evaluated as ‘-’ under the environmental protection criterion, that is, worse than the average level.

(3) Applicability

For two-stage pyrolysis, it is feasible to use this technique in remote areas. If the waste module recycling is carried out for the centralized PV power station, the recycling plant can be established nearby. Due to the various equipment used in the recovery process, such as milling machines and pyrolysis devices, transportation will bring some difficulties, but generally can be completed. However, if this technology is really used in large-scale industrial recycling processes, there will be a great demand for milling machines and pyrolysis equipment. At the same time, the pyrolysis process can only be carried out on a small scale, and the solar cell samples used need to be cut from the modules (Fiandra, 2019), rather than the whole PV modules. That makes it difficult to recycle on a large scale. In general, the evaluation result of two-stage pyrolysis under the criterion of applicability is ‘-’, which is worse than the average level.

For mechanical delamination of high voltage pulses, the technique can also be used in remote areas. Similar to two-stage pyrolysis, if module recycling is needed for centralized PV power stations in remote areas, a recovery plant can be built nearby. The instruments used for recycling are not a big problem in terms of transport. However, after the components are pulverized at high voltage pulses, a large number of sieves are needed to sift out the different recycled materials (Akimoto, 2018). It's a very meticulous process.

Predictably, its industrial batch processing is very difficult. In general, the evaluation result of high voltage pulse under the applicability criterion is '-', that is, worse than average stage.

For chemical delamination technology using organic reagents, it is suitable for use in remote areas. Similar to the other two technologies, if a centralized PV plant needs to recover used modules on a large scale, a recycling plant using chemical delamination technology can be located nearby. Since the core of the technology is the TCE reagent, it is necessary to ensure a large supply of reagents. In addition, the technology is suitable for large-scale recovery because although there is a large demand for organic reagents due to the large number of modules to be recovered, the reagent itself is low cost (Chemical Book, 2023). Overall, recycling technology that uses organic reagents to achieve chemical delamination score a '+' under the criteria of applicability, that is, better than average level.

(4) Technical effectiveness

As mentioned earlier, the separation rate of modules is the primary metric in evaluating this criterion. For the two-stage pyrolysis, the EVA layer contained in the module is completely degraded and the layer is completely separated from the solar cell (Fiandra, 2019), so the separation rate is 100%. Therefore, the evaluation result of two-stage pyrolysis under the criterion of technical effectiveness is '⊕', which is the optimal level.

For the high-voltage pulse method, it selectively separates and recycles the various materials by breaking up the PV panels, in which case the layers are not separated, but uniformly broken. Therefore, the separation rate is no longer applicable. However, by sifting, materials with recycling value such as silver, silicon powder and copper can be collected respectively (Akimoto, 2018), the overall technical efficiency is relatively high. The final evaluation results in a '+', that is, better than the average level.

For the chemical delamination technology, the PV panel can be completely separated in two hours with TCE as the reagent at the right reaction temperature and reagent concentration. Therefore, the separation rate is also 100%. The evaluation result of this technology under the criterion of technical effectiveness is '⊕', that is, the best level.

(5) Other social factors

For the two-stage pyrolysis technology, it is generally accepted by the public. Although no pollutants are produced in the milling process of the first stage, the second stage pyrolysis process will produce volatile products that are harmful to the environment, and whether they can be effectively treated will be a concern of the public. The method of separating PV modules by pyrolysis has been adopted by some projects. For example, China has funded a complete set of technology and equipment project for the recycling and treatment of c-Si PV modules, which uses the module separation method of pyrolysis (Innovation China, 2022). On the whole, the evaluation result of the technology under the evaluation criteria of other social factors is ‘0’, which is equal to the average level.

As for the mechanical delamination technology of high voltage pulse, it is relatively easy to be accepted by the public because of its low cost and no pollutants produced in the processing process. On the other hand, mechanical delamination technology has been paid more attention by some companies. For example, Changzhou Ruisai Environmental Protection Technology Co., LTD., based on mechanical delamination technology, has built a complete set of intelligent equipment for dismantling and fully automatic material sorting demonstration line (Ruisai Environmental Protection, 2023c), which has gained experience for further expanding the processing scale in the future. The technology is evaluated as ‘+’ on the criterion of other social factors, i.e., better than the average level.

For chemical delamination technology, organic reagents are inherently dangerous, so it is difficult for the public to accept. On the other hand, the technology is currently mostly done in laboratories rather than being used in batches by enterprises. In general, the chemical delamination technology is evaluated as ‘-’, i.e., worse than average on the criterion of other social factors.

The evaluation of the three module delamination technologies in step 1 under each criterion has been completed. The results are shown in Table 5. As can be seen from the table, each technology gets a ‘⊕’. Both thermal delamination and chemical delamination technology have two evaluation results of ‘-’, the difference is that thermal delamination received one more ‘0’ than chemical delamination. But overall, the evaluation performance of the two was similar. Moreover, mechanical delamination performed better across the criteria, earning three ‘+’ and the fewest ‘-’. However, the applicability of the technology may become an obstacle to the large-scale use of mechanical delamination. The final scores for each technology are calculated and discussed in section 3.5.

Table 5: Evaluation results for each technology in Step 1

Technology / Criterion	Thermal delamination (Two-stage pyrolysis)	Mechanical delamination (High-voltage pulse)	Chemical delamination (Organic reagents)
Economy	−	+	0
Environmental protection	0	⊕	−
Applicability	−	−	+
Technical effectiveness	⊕	+	⊕
Other social factors	0	+	−

3.4.2 Step 2: Solar cell recycling

Table 6: Recovery techniques to be evaluated in Step 2

Technologies
Wet metallurgy
Electrochemical assisted leaching
Wire explosion (High-voltage pulsed discharge)

(1) Economy

The process flow of recycling valuable metals in solar cells by hydrometallurgy is shown in Figure 6. It can be seen that the solar cells are first immersed in a solution of nitric acid for an hour, followed by a process to extract the various metals using different reagents (Jung, 2016). The whole recovery process involves many kinds of reagents and is relatively complex, so the recovery cost is high. On the other hand, the purity of silver extracted by this technology is up to 90%, the purity of aluminum is up to 94%, and the purity of copper is up to 79% (Jung, 2016), which has a high recovery yield. In summary, the evaluation result of hydrometallurgical technology under the economic criterion is '0', that is, equal to the average level.

The electrochemical assisted leaching uses boron-doped diamond as electrode and sulfuric acid as oxidant to recover silver and copper from solar cells (Wang, 2022). Since the oxidants used in this method are regenerated in the developed process, no additional chemical agents are required to be added (Modrzynski, 2021), thus the recovery cost is low. From the perspective of recovery income, the recovery rate of silver is 88% and that of copper is 99%, both showing a relatively high level. Although there are not many kinds of valuable metals recovered, the value of these two metals is high enough and the recovery income is high on the whole. Based on the above analysis, the evaluation result of electrochemical assisted leaching technology under the criterion of economy is '+', that is, higher than the average level.

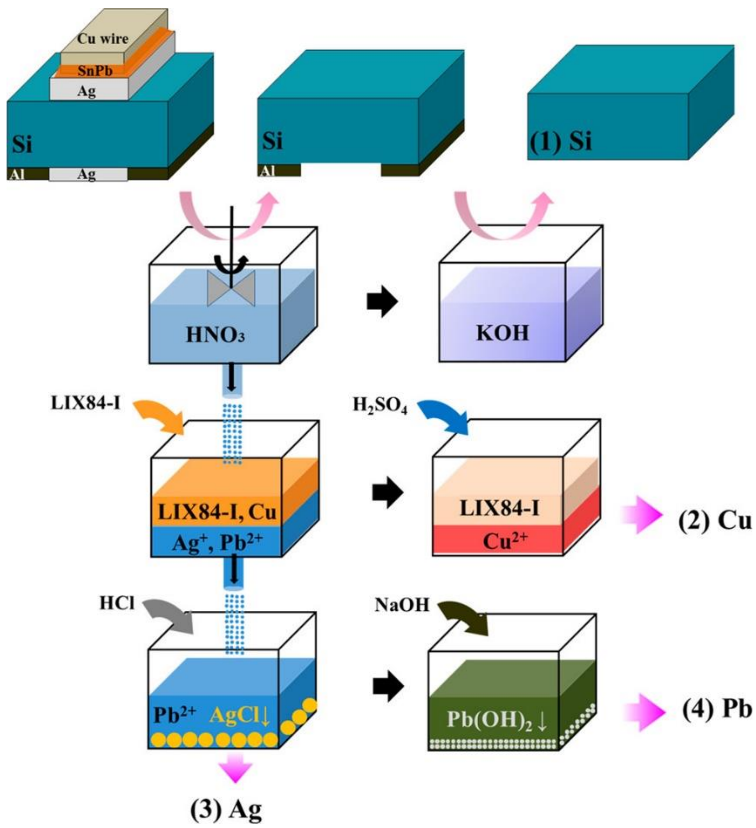

Figure 6: Recycling process of different metals (Jung, 2016)

The wire explosion technology directly separates and recovers silver particles by high voltage pulse discharge (Lim, 2021). Its circuit diagram is shown in Figure 7. Recovery cost is low because the process does not involve the addition of chemical reagents, nor does it require disposal of liquid waste, and the circuitry is not complex. However, this technology only focuses on the recovery of silver, ignoring other metals, and the recovery rate of silver is only 69% (Lim, 2021), thus the recovery efficiency is low. Overall, the technology rated '-' on the economy scale, which is worse than the average level.

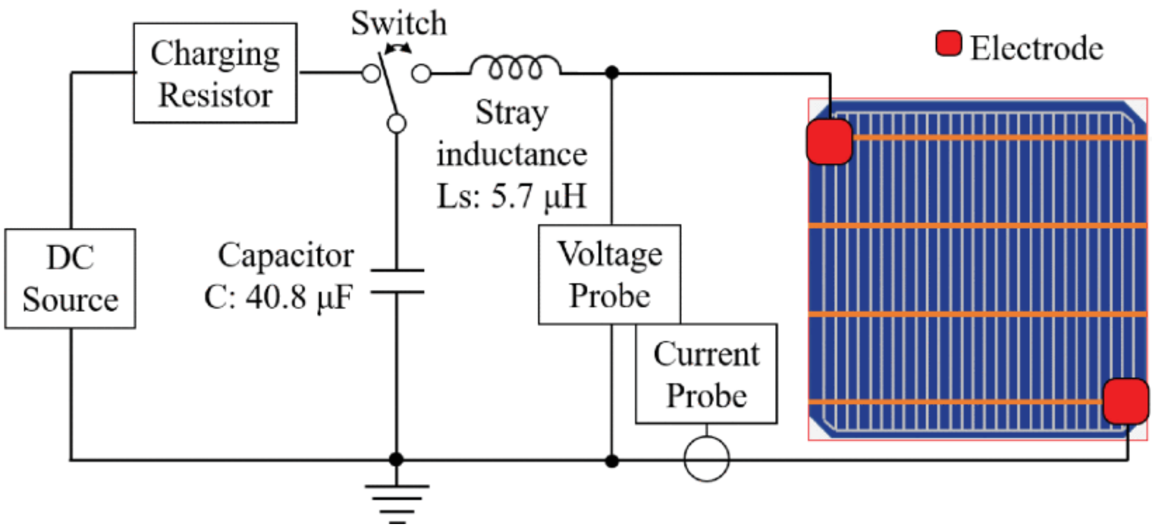

Figure 7: Circuit diagram of wire explosion technology (Lim, 2021)

(2) Environmental protection

For hydrometallurgy technology, due to the use of nitric acid, toxic acid fog containing nitrogen oxides will be produced in the recovery process (Jung, 2016), which has great harm to the environment. In addition, for the recovery of different kinds of metals, the technology uses different chemical reagents, such as sulfuric acid, hydrogen chloride, sodium hydroxide, etc., these reagents will form waste liquid after the recovery (Jung, 2016), which needs to be properly disposed to avoid harm to the environment. In general, hydrometallurgical technology is evaluated as '-' under the criterion of environmental protection, i.e., worse than the average level.

For electrochemical assisted leaching technology, although this recovery method constitutes a cyclic process, that is, no additional chemical reagent is added (Modrzynski, 2021), the treatment of leaching reagent after the completion of recovery is still a problem that needs to be considered. Overall, the technology scored a '+', or better than the average level, on the environmental protection criterion.

For the wire explosion technology, it is completely green and pollution-free because it relies on the circuit to complete, and does not involve the addition of chemical reagents, and the recycling process does not produce harmful waste to the environment. Its assessment result under the environmental protection criteria is '⊕', that is, the best.

(3) Applicability

Hydrometallurgy is feasible in remote areas. Due to the large number of chemical reagents involved in the recovery process, regional factors should be considered in the disposal of waste liquid to avoid the impact on public life. The centralized PV power stations are mostly located in the northwest of China, which is vast and sparsely populated, and there are not many residents around the PV power stations, so it is suitable to build recycling plants nearby. Hydrometallurgy, on the other hand, has a well-defined process, and although it has many steps, it is easy to batch process, forming a complete set of recovery treatment lines. In this case, hydrometallurgy can be used for large scale recovery of used modules. In general, wet metallurgy technology is evaluated a '+' on the criterion of applicability, i.e., better than the average level.

Electrochemical assisted leaching technology is also suitable for use in remote areas. On the one hand, the disposal of leach waste produced in the recycling process is suitable for disposal away from residents. On the other hand, the recycling process does not involve much equipment or chemicals, so it is feasible to set up recycling plants near centralized PV power stations. However, the module area processed by this technology is small, and the recovery process lasts for a long time (Modrzynski, 2021). The overall recovery efficiency is low, and it is not suitable for large-scale recovery. Therefore, it is unrealistic to be the main technology for the disposal of waste modules in centralized PV power stations. Based on the above analysis, the evaluation result of electrochemical assisted leaching technology under the criterion of applicability is '-', that is, worse than the average level.

Remote areas are less of an issue for wire explosion technology because the capacitive energy discharge circuit used for recovery is easy to build and is not affected by regional factors. The technology is used to process the entire solar cell, but the process takes a long time, so its suitability for large-scale solar module recycling has yet to be proven. Based on the above considerations, the evaluation result of this technology under the criterion of applicability is '0', which is the average level.

(4) Technical effectiveness

Among the technologies in step 2, the evaluation of technical effectiveness mainly focuses on the parameter of metal recovery. For hydrometallurgy, the recovery rate of silver is up to 90%, copper 79% and aluminum 94% (Jung, 2016), of which copper is relatively low. However, considering that silver is the element with the highest recovery value and its recovery rate is maintained at a high level in hydrometallurgy, the technology is evaluated as ‘+’ under the criterion of technical effectiveness, which is better than the average level.

For electrochemical assisted leaching technology, silver and copper are the main metals recovered. Among them, the recovery rate of silver reached 88% and that of copper reached 99% (Modrzynski, 2021), both of which reached very high levels. Therefore, the result of this technology under the evaluation criterion of technical effectiveness is ‘+’, that is, better than the average level.

As for the wire explosion technology, silver is the only metal it focuses on during recovery, and the recovery rate is not high, only 69% (Lim, 2021), so the result of this technology under the evaluation criterion of technical effectiveness is ‘-’, that is, worse than the average level.

(5) Other social factors

Hydrometallurgy is less acceptable to the general public due to the large number of chemicals involved and the disposal of harmful gases and waste liquids during the process. However, this technology has been developed over a long period of time, with many scholars working on improving silver recovery rates and using more environmentally friendly reagents (Wang, 2022), so it will be a recycling technology that companies will try to use in the foreseeable future. Overall, the evaluation result of the technology under the criteria of other social factors is ‘0’, which is the average level.

As for electrochemical assisted leaching technology, it can constitute a cyclic process itself, and it uses few chemical reagents and has limited impact on the environment. Therefore, it can be accepted by the public. However, this technology is still being studied in the laboratory and has not been used in batch processing. In summary, the evaluation result of this technology under the criterion of other social factors is ‘-’, that is, worse than the average level.

It is obvious that the wire explosion technology is easy to be accepted by the public because it is free from chemicals and is green and pollution-free. However, similar to electrochemical assisted leaching, this technology lacks practical application and is only studied and tested in the laboratory. In summary, the evaluation result of wire explosion technology under the criterion of other social factors is ‘0’, that is, the average level.

The evaluation of three technologies for recycling valuable metals from solar cells in step 2 under each criterion has been completed. The results are shown in Table 7.

Table 7: Evaluation results for each technology in Step 2

Technology / Criterion	Wet metallurgy	Electrochemical assisted leaching	Wire explosion (High-voltage pulsed discharge)
Economy	0	+	−
Environmental protection	−	+	⊕
Applicability	+	−	0
Technical effectiveness	+	+	−
Other social factors	0	−	0

As can be seen from the table, the wire explosion technology received the most ‘0’ and ‘-’, which means that it will score lower than the other two technologies. Neither hydrometallurgy nor electrochemically assisted leaching has achieved optimal evaluation results under either criterion. Hydrometallurgy receives fewer ‘+’ and ‘-’ but more ‘0’ than electrochemically assisted leaching. It is worth noting that hydrometallurgy has obtained a ‘+’ in the two criteria with maximum weight: applicability and technical effectiveness, which will improve its final score a lot.

3.5 A short discussion

Table 5 and Table 7 show the evaluation results of the technologies in step 1 and step 2, respectively. With these evaluation results, combined with the score represented by each symbol and the weight of each criterion in the total score, the final score of technologies under the evaluation system can be calculated. The results are shown in Table 8.

Table 8: The final score of the technology being evaluated

Step 1	**Technology**	**Thermal delamination (Two-stage pyrolysis)**	**Mechanical delamination (High-voltage pulse)**	**Chemical delamination (Organic reagents)**
	Score	3.05	3.65	3.45
Step 2	**Technology**	**Wet metallurgy**	**Electrochemical assisted leaching**	**Wire explosion (High-voltage pulsed discharge)**
	Score	3.35	3.2	2.85

Before comparing the evaluation results, one point needs to be emphasized again. Although there are seven technologies selected in table 2, in the second step, chemical etching is the choice in most cases for silicon wafer recycling, so this thesis does not compare and evaluate it with other silicon wafer recycling technologies. This is why only six technologies are represented in the evaluation results table. It can be clearly seen from table 8 that in the first step, mechanical delamination gets the highest score, chemical delamination comes second, and thermal delamination gets the lowest score. In the second step, hydrometallurgy obtained the highest score, followed by electrochemical assisted leaching, and wire explosion's score was the lowest. By combining the two technologies with the highest scores, a complete set of upcycling technology can be obtained. The first step is to complete the module delamination by mechanical method, so that the EVA layer is completely separated from the solar cell layer. Then, in the second step, the silicon wafer is recovered by chemical etching and the valuable metal is recovered by wet metallurgy.

It is worth noting that both mechanical delamination technology and wet metallurgy technology are still worthy of improvement. A significant problem for mechanical delamination is that batch processing is difficult, so how to improve it to make it suitable for large-scale recycling of waste modules is a problem to be solved in the future. For wet metallurgy technology, the problem of how to effectively deal with the harmful gas and waste liquid produced in the recovery process is of great concern. Once this problem is well solved, wet metallurgy technology can be used on a large scale.

4. The analysis of the case of PV module recycling in China

After the evaluation of various recycling technologies, this chapter focuses on the analysis of TIS framework. First, in order to better analyze each building block and influencing condition, section 4.1 analyzes key participants in the entire process of PV module recycling based on the stakeholder map. Next, section 4.2 analyzes and evaluates each building block based on the actual situation of PV recycling in China. Sections 4.3 focuses on influencing conditions in the TIS framework, which are analyzed one by one. Finally, section 4.4 explores the relationships between building blocks and influencing conditions. In this chapter, two research sub-questions are answered, namely:

Sub-question 4: How well is the Technological Innovation System for waste crystalline silicon PV module recycling technology developed in China?
Sub-question 5: What is influencing the current development of the Technological Innovation System for waste crystalline silicon PV module recycling technology in China?

4.1 Stakeholder map

In this section, a stakeholder map is designed to identify key actors in China's PV module recycling industry and their relationships, thus laying a foundation for analyzing and evaluating building blocks and influencing conditions in TIS framework. The stakeholder map is shown in Figure 8. Different colors represent different interested parties, and the various connections between them are indicated by arrows and text. It should be pointed out that the information of the actors represented in italics cannot be found, so it is not possible to confirm whether they are really working in the network at the current stage, and their connections to other actors are indicated by dotted lines.

The green modules represent policy makers and the standard setter. Policy makers include China's National Energy Administration and the Ministry of Industry and Information Technology. Typical policies include the regulations on the development and construction of PV power stations issued by the National Energy Administration in 2022 (National Energy Administration, 2022b), and a circular jointly issued by the Ministry of Industry and Information Technology (MIIT) on promoting the coordinated development of the PV industrial chain and supply chain (MIIT, 2022a). They all explicitly mention and encourage the recycling of PV power stations and accelerate the technology, standards and industrialization research of waste module recycling. There are many other sectors that policy makers are involved in, but not all of them are listed in the figure for simplicity. The standard setter is usually the Standardization Administration of China, which approves and issues national standards related to PV recycling (Standardization Administration, 2023).

The yellow modules are enterprises that provide PV module recycling services, which are also key actors in the stakeholder map. It can be divided into two categories: one is China's leading PV enterprises, and the other is high-tech enterprises specializing in PV recycling. They have a good cooperative relationship, and both focus on PV module recycling technology research and development. For China's leading PV enterprises, Jinko Solar is selected as an example, while for enterprises specializing in PV recycling, Changzhou Ruisai Environmental Protection is selected as an example. The above enterprises have certain differences in the main business in the field of PV recycling. First of all, for the leading PV enterprises, their main identity is the PV module supplier. These companies are responsible for many large centralized PV projects in northwest China. For example, Jinko Solar completed a 110MW PV project in Jinchang, Gansu Province, in 2013 (Jinko Solar, 2020b). These centralized PV power stations are the main supply source of used PV modules, which is represented by the gray module in the stakeholder map. As can be seen from Figure 8, on the one hand, China's leading PV enterprises have built these centralized PV power stations and are responsible for the recycling of the power stations when their service life reaches a certain number of years. On the other hand, these centralized power stations provide companies with waste modules. After recycling, some of the materials, such as aluminum frames, can be reused to make new modules (NetEase, 2023b). The recycled silicon, which cannot be reused to make crystalline silicon (Sina News, 2023), will be used in the chemical, electronics and metallurgical industries. In summary, the main businesses of leading Chinese PV enterprises involved in module recycling are listed as follows:

1. Dismantlement and assembly disposal of waste centralized PV power station
2. The sale of recycled industrial silicon
3. The reuse of other materials obtained from recycling, i.e., for the production of new modules.

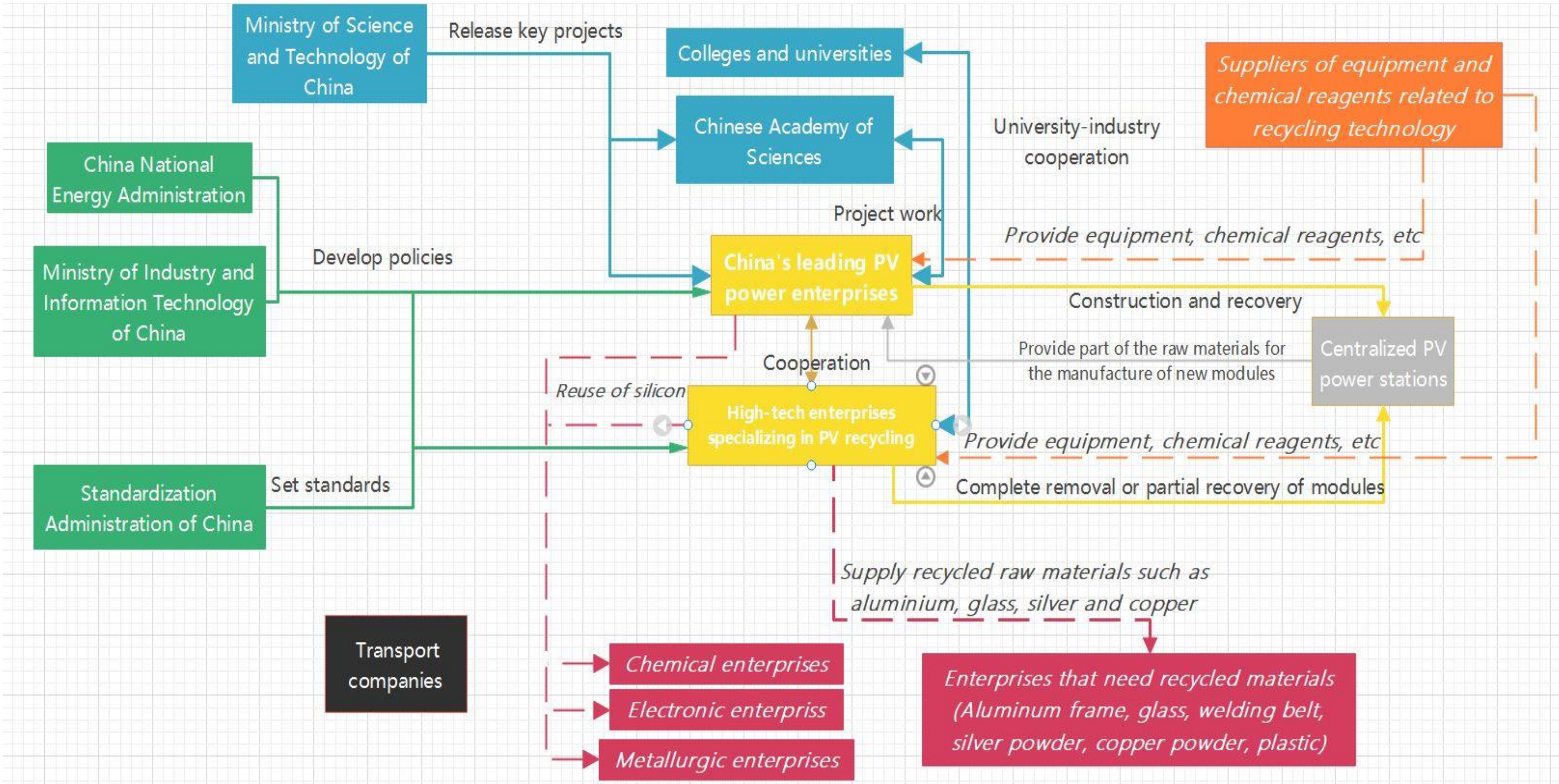

Figure 8: Stakeholder map of China's PV module recycling industry

For high-tech enterprises specializing in PV recycling, the main businesses are different. Take Changzhou Ruisai Environmental Protection Technology Co., Ltd. as an example, its businesses are divided into four categories (Ruisai Environmental Protection, 2023b). The first is the engineering category, including the overall buyback and dismantlement of retired PV plants, which can be seen in Figure 8. The second is environmental protection, that is, the disposal of waste PV modules. The third is the material category, that is, the processing and purification of related materials obtained after the dismantling of PV modules. Finally, there is the trade category, which focuses on the sale of recycled materials. For clarity, these businesses are listed below:

1. Buyback and disassembly of retired PV power stations (engineering)

2. Disassembly and disposal of retired PV modules (environmental protection)

3. Processing and purification of dismantled PV materials (materials)

4. Sales of recycled materials (trade)

The red modules in Figure 8 represent the enterprises that trade materials with PV recycling enterprises, that is, the demand side for recycled materials. As mentioned above, since the recovered silicon cannot be used again in the PV industry, both leading PV enterprises and high-tech enterprises focusing on PV recycling realize the reuse of silicon by selling the recovered silicon materials. The targets of sales include chemical enterprises, electronic enterprises and metallurgical enterprises, as shown in Figure 8. However, when it comes to specific companies in these industries, the current information does not give an exact list. Most of the leading PV companies see this business as the future direction of development (NetEase, 2023b). This is because it is matched by related technology research and development services. Recycling silicon, for example, involves the corresponding down cycling technology. For the reuse of silver, purification technology needs to be further developed to meet a wider range of industrial needs (NetEase, 2023b). These technologies still need time to accumulate. On the other hand, high-tech enterprises focusing on PV recycling try to sell aluminum, glass, silver, copper and other materials they get from recycling to enterprises in need since these materials have no use for themselves. This is reflected in stakeholder map that PV recycling enterprises provide raw materials for enterprises that need aluminum frame, glass, welding belt, silver powder and copper powder. Similar to the situation mentioned earlier, these businesses are also in an unclear state for high-tech enterprises specializing in PV recycling. Although it is assumed that these companies need to carry out the business of selling recycled materials in order to make a profit (Ruisai Environmental Protection, 2023b). However, with the current information, it is difficult to give a detailed list of companies that need relevant materials. To sum up, whether it is for PV leading enterprises or enterprises specializing in PV module recycling, the reuse of recycled materials is still in an unclear state. Relevant actors do not actually exist in the stakeholder map, so they are indicated in italics.

Blue modules are scientific research institutions, universities and other units that have close cooperation with leading PV enterprises, as well as PV recycling high-tech enterprises. In addition, the Ministry of Science and Technology of China is also included in the blue module. The relationship between these actors and their relationships with other stakeholders is as follows: First, the Ministry of Science and Technology initiated a key project on ‘Renewable energy and hydrogen energy technology’ (The State Council, 2019), which includes ‘Complete set of technologies and equipment for the recycling and processing of crystalline silicon photovoltaic modules’. Then the Chinese Academy of Sciences jointly with a number of PV enterprises and research institutes to undertake and complete the project. Among the enterprises involved, there are many leading PV enterprises, such as Jinko Solar (NetEase, 2023b). On the other hand, high-tech enterprises specializing in PV recycling have relatively close cooperation with many colleges and universities. For example, Ruisai Environmental Protection has a good industry-university-research cooperative relationship with Nanjing University of Aeronautics and Astronautics, China University of Mining and Technology and some other universities (Ruisai Environmental Protection, 2023a).

The orange modules represent enterprises that provide equipment and chemical reagents related to recycling technology for PV enterprises and recycling enterprises. Their presence ensures that the recycling process goes smoothly. It seems that the supply of equipment and reagents by these enterprises is only necessary when module recycling is carried out on a large scale. Otherwise, PV recycling enterprises have the ability to develop relevant equipment on their own (Science Net, 2022). Therefore, these actors are also highlighted in italics to indicate that they are in a state of uncertainty. The black module indicates the transport company. On the one hand, they transport used PV modules for processing and recycling. In this case, the transport company links the yellow and gray modules shown in Figure 8. On the other hand, they transport recycling-related equipment, chemicals, etc., connecting the yellow and orange modules in Figure 8. These relationships are somewhat complex, and marked with lines and arrows between modules will make the stakeholder map look confused, so relevant identification is not omitted in Figure 8. It is worth noting that some of the actors whose importance is not yet certain are not identified in Figure 8. For example, whether companies that specialize in handling waste generated during recycling should be considered as interested party. At its core, the uncertainty stems mainly from whether these companies are necessary. Take waste recycling as an example, if the technology used by the PV recycling company already involves waste disposal, there is no need to turn to the relevant professional enterprises. In this case, they naturally cannot act as the interested party. For the sake of rigor, these enterprises whose necessity is yet to be proved are ignored in the stakeholder map.

Overall, stakeholder map involves a large number of actors, which can be divided into policy and standard makers, enterprises engaged in PV recycling, centralized PV power stations, universities and scientific research institutions, enterprises with demand for recovered materials and supporting enterprises (equipment, chemical reagent suppliers, transport companies). They are closely related to each other. However, some actors, including the demand side of recycled materials, the supply side of recycling equipment and chemical reagents, need more information on their authenticity and links with other actors. After the stakeholder map is designed, the analysis of each building block and influencing condition will become traceable.

4.2 Analysis of building blocks

4.2.1 Product performance and quality

This building block focuses on product performance and quality. If it lacks sufficient performance and quality, the product cannot achieve large-scale diffusion (Ortt, 2022).

China's research on PV module recycling technology is not early. In April 2019, a number of PV enterprises and scientific research institutes jointly undertook the project of ‘Complete set of technology and equipment for recycling and processing of crystalline silicon photovoltaic modules’, aiming to form a demonstration line for recycling and processing of crystalline silicon PV modules through a technical route of low energy consumption and low pollution (Science Net, 2022). By December 2022, the project was completed, and two PV module recycling demonstration lines based on different technical methods were built by Yingli Group and Jinko Solar respectively (Insight And Info, 2023). Considering the current situation, a number of PV companies are conducting research and development of recycling technology (NetEase, 2023a), but the integrity of their products is not yet known. In order to be more realistic and make the analysis convincing, the PV module recycling demonstration line built by two enterprises mentioned above is used as the analysis object in this section. The analysis of building blocks involving ‘products’ is also based on this. The main basis for judging the performance and quality of the product is the recovery rate of the materials in the PV module and the overall recovery rate of the module.

The first is the PV module recycling demonstration line built by Yingli Group in Baoding, Hebei Province, based on physical methods. It has successfully developed the core equipment for component disassembly and module delamination (Science Net, 2022). Data show that the total mass recovery rate of the recycling service provided by the demonstration line can reach 99.7%, and the recovery rate of valuable materials such as silver, silicon and copper can reach 94.3%, 97.7% and 97.1%, respectively (Science Net, 2022). These data show fully that Yingli Group can provide PV module recycling services with very high performance and quality, can well meet the needs of customers. The PV module recycling demonstration line based on chemical methods built by Jinko Solar breaks through the constraints of low-loss dismantling technology and equipment (Science Net, 2022), and can achieve a total mass recovery rate of 92%. In addition, the product also performs well in the recovery rate of valuable materials, especially the recovery rate of high value metal materials silver and copper, which can reach 95% and 98% respectively (Science Net, 2022). The recovery rate of silicon material reached 95%, which is also maintained at a relatively high level.

The PV module recycling products provided by the two companies evaluated are of international advanced level (Science Net, 2022). However, they are only a small part of the overall PV module recycling industry, and it does not prove that all other relevant companies have the ability to provide their target customers with products that satisfy them. In fact, since 2021, a large number of small workshops have flooded into China's PV module recycling market (NetEase, 2023a), and the recycling services they provide do not have performance and quality: they only disassemble and sell the most easily disassembled aluminum frames in the modules, and bury the remaining parts directly (NetEase, 2023a). These so-called products have neither performance nor quality to speak of, and are also causing great harm to the environment.

To sum up, in the Chinese PV module recycling market, there are several companies that can provide products that meet the needs of customers, ensure their performance and quality, and make them compatible with large-scale diffusion. However, the universality of the phenomenon has not been proven. At present, a large number of small and micro enterprises and self-employed individuals engaged in PV module recycling do not have the ability to provide products with excellent performance and quality. Therefore, the evaluation result of this building block is partially complete.

4.2.2 Product price

This building block requires the product to have a reasonable price relative to other competitive products. The price of a product includes the financial or non-financial investment to obtain and use the product, and if the price of the product is too high, it will discourage large-scale diffusion (Ortt, 2022).

First, the financial and non-financial costs of obtaining and using the product are broken down. As envisaged, financial costs can be divided into five parts: 1. Location and construction of PV module recycling plant. 2. The cost of equipment and chemical reagents used in the recycling process. 3. Cost of disposal of pollutants 4. Labor cost of disposal of waste modules. 5. R&D and testing costs invested in the early stage. Non-economic costs include: 1. The time cost of establishing a trusted relationship between a company and a centralized PV power station 2. The cost of time and effort to establish a long-term partnership with a company that buys the recycled materials. Both are about the non-economic cost of time and effort. As noted above, the costs cited remain within the envisaged range. It's hard to know how they actually perform. The two companies that built the PV recycling demonstration line are still the object of analysis in this subsection. The recycling demonstration lines built by them are located away from the urban area (Insight And Info, 2023), and the use cost of land resources is low. The cost of equipment and reagents used for recycling, the cost of treating pollutants, the cost of human resources needed for recycling and the cost of research and development of technologies are not yet known. The same is true of non-financial costs, but predictably, it takes a lot of time and effort to establish a good relationship with both centralized PV plants and downstream companies that need recycled raw materials.

For companies specializing in PV module recycling, in addition to the financial costs mentioned above, they also need to pay for procurement costs (NetEase, 2023a). Since 2021, a large number of actors have flooded into the PV recycling market, most of which do not have the main purpose of recycling PV modules, but pursue the profits obtained by reselling PV modules. This has led to a shift in the market model. Before 2021, PV power plants need to pay PV module recycling companies to dispose of waste modules. However, the current situation is that PV module recycling companies have to pay for procurement costs and first purchase waste modules from PV power stations (NetEase, 2023a). This undoubtedly brings huge costs to enterprises. According to estimates, the increase in procurement costs has led to a loss of 10% for every PV module recycled (NetEase, 2023a).

In summary, for the recycling products provided by China's leading PV enterprises, the cost is not yet available, so the price of its products is unknown. For high-tech enterprises specializing in PV module recycling, the high cost greatly limits the large-scale diffusion of products. Therefore, the evaluation result of this building block is incomplete, that is, incompatible with large-scale diffusion.

4.2.3 Production system

The focus in this building block is on production systems, which can produce a large number of products that ensure performance and quality. If production systems are missing, large-scale diffusion is hampered (Ortt, 2022).

Although a considerable number of enterprises in China have carried out layout and research and development of PV module recycling, there are not many completed PV module recycling demonstration lines (NetEase, 2023a). Since the module recovery demonstration line covers the complete module processing steps, the analysis of the production system should be based on them. This subsection still takes the two PV recycling demonstration lines built by Yingli Group and Jinko Solar as the analysis object. Yingli Group has built a demonstration line for module recycling based on physical methods, with an annual capacity of more than 10MW and a processing capacity of 1,000 tons. The chemical-based module recycling demonstration line built by Jinko Solar has an annual capacity of 12MW and a higher processing capacity (Insight And Info, 2023). From the data alone, these enterprises have initially built production systems. However, compared with the rapid growth of China's PV installed capacity every year and the number of retired modules rising year by year (NetEase, 2023a), such scale of production systems is far from meeting demand. Expanding the scale of production and increasing the number of enterprises with the ability to build production systems is the development direction of the PV recycling industry in the future.

In summary, the evaluation result of the production system as a building block is partially complete. Although two companies have already built small-scale demonstration lines for module recycling, there is still huge room for improvement in both scale and quantity.

Thus, this building block is partially compatible with the large-scale diffusion of the product.

4.2.4 Complementary products and services

This building block focuses on supporting products and services for the development, production, distribution, use, maintenance, and disposal of innovations. When these complementary products and services are unavailable or too expensive, large-scale diffusion is hampered (Ortt, 2022).

There are many supporting services related to PV module recycling. The first is the inspection of the modules in the centralized PV power station. This work is usually carried out once a year, and is mainly for PV modules that have been in operation for a long time. The whole inspection involves many detection items, such as appearance inspection, scanning inspection, power attenuation, etc., which need to be inspected regularly (NetEase, 2023b). Once problems are found, the number of detections can be appropriately increased. According to the current situation, this complementary service is mainly completed by third-party testing organizations (Interviewee A). The owner of the PV power station commissions the inspection party to conduct a 'post-occupancy evaluation' of the PV power station, that is, to inspect it regularly after a period of use. These third-party organizations have a full range of testing items and methods, and have very rich experience in providing testing services (Interviewee A). Thus, the first complementary product and service is available.

The second is the repair of PV modules. Not all PV products that look substandard meet the conditions for scrapping (NetEase, 2023b). In this case, a simple fix becomes an effective way to deal with it. However, the difficulty of repair varies with different components of the PV module. The replacement of cables, the repair of junction boxes and backplanes, etc., can be done on-site, but to replace or repair solar cells, they need to be done in a professional workshop. According to the current situation, new modules provided by PV module suppliers have a certain period of quality assurance. Taking Jinko Solar, a typical large-scale PV manufacturer, as an example, the company will issue a quality guarantee certificate to the original purchaser of the module, and for modules that do not meet the quality guarantee, the company will also provide repair, replacement and other relief services (Jinko Solar, 2020a). In general, this complementary service will be compatible with large-scale diffusion.

The third supporting service is the treatment of pollutants produced during the recycling process. As mentioned in Chapter 3, when hydrometallurgy is used in the second step of PV module recycling, i.e., the reuse of solar cells, both the chemicals involved themselves and the waste liquid form environmentally harmful pollutants. Therefore, if these recycling technologies that produce pollutants are used, supporting pollutant treatment technologies need to be developed. At present, a more significant problem is that if pollutant treatment is also considered in the cost of PV module recycling, its economy has the risk of further reduction. If looking for enterprises specializing in the treatment of pollutants to contract, the corresponding cost needs to be borne by the owner of the centralized PV power station on the basis of the original. In addition, for Jinko Solar, which currently uses the chemical method to build a demonstration line for module recycling (Insight And Info, 2023), there is a lack of sufficient information sources to prove that the company can provide a complementary service to deal with the pollutants generated by recycling. In general, it is not easy to achieve the supporting service of pollutant treatment in the recycling process.

In summary, the analysis result of the building block of ‘complementary products and services’ is partially complete. In those complementary services, in addition to the regular detection of PV modules and PV module maintenance are easy to obtain, the rest of the supporting services have the risk of increasing costs. Although improved technologies, such as the treatment of pollutants during recycling, can reduce the difficulty and cost of obtaining complementary services, for now, the relevant research needs to be further developed.

4.2.5 Network formation and coordination

In order for products to proliferate on a large scale, actors need to fully coordinate their activities to develop, produce, distribute, repair, maintain and dispose of products (Ortt, 2022).

The suppliers of waste PV modules are relatively simple, that is, the owner of centralized or distributed PV power station. As this thesis focuses on the recycling of centralized PV power stations, they provide all the waste PV modules. Although the owners of centralized PV power plants are also target customers, the waste modules they provide guarantee the production of products to a certain extent, as all the recycling services are based on PV modules. Notably, there are two types of supply: one is to turn over the entire plant to a PV module recycling company when the centralized PV plant reaches the end of its life span, and the other is to provide some damaged or used modules in the power station to PV module recycling companies (Ruisai Environmental Protection, 2023b). According to the perspective of practitioners in the PV industry, the owners of centralized PV power stations pay fees to PV module recycling enterprises, and then the waste modules are handled by these enterprises, which is the mainstream form of the future (Interviewee A). This is mainly due to the high price of centralized PV power stations to change hands, in addition to PV leading companies, few module recycling companies are willing to bear this cost (Interviewee A).

Some other types of actors are also worth watching. The first is the supplier of PV recycling equipment and chemical reagents. They guarantee equipment and materials for leading PV enterprises and high-tech enterprises specializing in PV recycling. Then there are the transport companies. Considering that centralized PV power stations are mostly located in the northwestern part of China (Liu, 2019), which is relatively remote, the whole supply chain should not lack transportation companies. For PV recycling enterprises, if they choose to build a recycling plant near the centralized power station, they need transportation companies to transport materials for plant construction, and at the same time transport a large amount of recycling and processing equipment and chemical reagents to these areas. However, if the PV recycling enterprise adopts the method of first shipping the waste modules back to the company and then unified processing, a large number of waste modules still need to be transported. Transport companies thus play an indispensable role. Finally, solid waste treatment enterprises. Considering that not all PV recycling enterprises are developing recycling technology and taking into account the treatment of pollutants, the assistance of solid waste treatment enterprises may be needed (NetEase, 2023b). However, this actor is not as indispensable as transportation companies and recycling equipment suppliers. When PV recycling companies have sufficient capacity to deal with pollutants, the involvement of solid waste treatment companies is no longer necessary.

Due to very limited sources of information, it is not possible to list which of these various actors are included. In addition to solid waste treatment enterprises, suppliers of recycling equipment and chemical reagents, as well as transportation companies, are indispensable in the large-scale diffusion of PV module recycling. This is because in the face of a large number of waste modules, the establishment of large-scale recycling requires a sufficient number of recycling equipment and chemical reagents, only by PV recycling enterprises to develop their own is impossible. In addition, when module recycling is carried out on a large scale, cross-regional transport of a large number of used modules will often occur.

In this process, transportation companies will play an important role.

Overall, the network is still in the process of being formed. It does not mean that once some actors intervene, it remains unchanged. Moreover, in China, the current supply mode is that each participant intervenes scattered (NetEase, 2023b), with fewer types of actors but a considerable number. The possibility that some actors may withdraw under certain circumstances cannot be ruled out. Therefore, it is difficult to say that the network has been formed, since the PV recycling in China is still in its infancy, and the operation mode is still likely to change greatly. The same is true of coordination among actors, which is emerging but unformed. The transportation company coordinates with recycling equipment suppliers, centralized PV power stations and PV recycling enterprises to ensure timely delivery of used PV modules or recycling and processing equipment. Recycling equipment suppliers coordinate PV recycling enterprises and centralized PV power stations to ensure the delivery of products and services. Solid waste treatment companies coordinate centralized power stations and photovoltaic recycling companies to reduce pollutant generation when recycling technology does not involve solid waste treatment. However, the above coordination tends to be more idealistic. Taking transport companies as an example, in actual operation, they will encounter policy obstacles when transporting solid waste across regions (Xinhua, 2023b).

To sum up, although the various actors and their coordination relationships are envisioned to work perfectly, as an industry in its infancy, the uncertainty of PV recycling itself will have an impact on the formation of networks and coordination relationships among actors. At the same time, the limited information sources in the study limited further judgments on network formation and cooperation. Therefore, the analysis result of this building block is partly complete.

4.2.6 Customers

The customer is an important building block. When they fully understand the product, discover its advantages, and have the knowledge, means, and willingness to use the product, they will change from potential customers with innovative needs to real customers. Without customers, there is no way to spread innovation on a large scale (Ortt, 2022).

No matter for China's leading PV enterprises, or focus on PV recovery of high-tech enterprises, customer segmentation is clear. First, for China's leading PV companies, their target customers are relatively simple. They themselves play the role of PV module manufacturers, when it comes to module recycling, there will be different recycling modes, namely commissioned recycling, independent recycling and joint recycling (NetEase, 2023b). As far as commissioned recycling is concerned, centralized PV power stations built by these large PV enterprises are handled by other companies with recycling qualifications. This process does not involve any customers for large PV manufacturers. It is also possible for the owners of other centralized PV plants to hand over their recycling projects to large PV producers. In this case, the owner of the centralized PV power station is the customer. In terms of independent recycling, these large PV enterprises complete the recycling of the centralized PV power stations they build by themselves. In this case, the customer is themselves. The last recycling mode, also known as joint recycling, means that these large-scale PV manufacturers and high-tech enterprises or related units specializing in PV recycling jointly complete the recycling of centralized PV power stations. It is worth noting that the owners of centralized PV plants are potential customers of large PV companies, both for commissioned and combined recycling modes. Perhaps the PV modules in these plants are not supplied by the big PV manufacturers, but the trust in their technology is left to them to recycle the plants. In addition to silicon, other materials recycled by large PV companies, including rate frames, glass and metals, can be reused in the production of new modules (Xinhua, 2023b). Silicon, however, will be used as an industrial material because it cannot be reused, that is, remade into monocrystalline or polycrystalline silicon (Xinhua, 2023b). Therefore, leading PV companies will provide degraded use of silicon materials for their applications in the aluminum alloy industry and chemical industry (NetEase, 2023b). In this case, companies in the aluminum alloy industry and chemical industry that have demand for industrial silicon will be potential customers of the leading PV companies.

For high-tech enterprises specializing in PV recycling, customer segmentation is slightly different. On the one hand, the services and products provided by these companies, namely the buyback and dismantling of PV plants, the dismantling and disposal of PV modules, and the recycling of related materials, are targeted at the owners of centralized PV power plants (Ruisai Environmental Protection, 2023b). On the other hand, like the leading PV companies, they target industrial silicon buyers after disposing of the silicon in waste modules. The difference is that other materials recovered, such as glass and metal, are not necessary for PV recycling companies to reuse, so they can only be sold. The target customers of this part of business are the corresponding material demand companies.

Whether the potential consumers have the knowledge, means and willingness to use the product is the key to whether it can be converted into real customers. Centralized PV plant owners do not need to have unique knowledge, as they are not involved in the service and process of recycling waste modules in PV plants. What they need to fully understand and compare is the quotation offered by different PV recycling companies, as well as the recycling rate of the relevant materials. This requires that centralized PV plant owners have access to information. In this regard, PV leading enterprises have more advantages than PV recycling enterprises. On the one hand, the leading enterprises have a certain brand effect (NetEase, 2023b). As the top several PV suppliers in China, they are well-known in the industry. On the other hand, recycling companies do not advertise enough to make centralized power plant owners fully aware of their products and services, or the small scale of the company leads to customer concerns about risks. In this case, the owner of the centralized PV power plant may choose another company due to lack of sufficient knowledge of the product. However, whether it is a leading PV enterprise or a small PV recycling enterprise, customers have enough means to obtain products. Centralized PV plant owners can select a portion of the waste modules, choose a PV recycling company to ‘trial’, learn the advantages before deciding whether to entrust the entire plant recycling work to them. And the willingness of owners of centralized PV plants to use their products is strong enough. Although there are many PV recycling enterprises to choose from, their products, namely recycling services, are consistent, which is the only way for customers to seek solutions to dispose of used PV power stations.

It's a different story for other potential customers, buyers of recycled materials. Take the demand of silicon material as a typical case to analyze. They don't lack product knowledge. With industrial silicon as the base material for their industrial production, these customers are well aware of information such as types and prices of silicon (Sina Finance, 2022b). They also have ample means (Ruisai Environmental Protection, 2023b), notably from PV recycling companies, to obtain the corresponding product (industrial silicon), since it's easy to get cooperation information from their website. However, a more significant question is whether these silicon demand companies will be willing enough to capture the industrial silicon recovered by PV recycling companies. Large industrial silicon producers have a significant competitive advantage because of their long history of rising production and stable costs (Pacific Securities, 2022). It remains to be seen whether the quality and price of industrial silicon produced by PV recycling are attractive enough compared with them. And with prices and production stable, silicon demand is unlikely to try to find new suppliers.

To sum up, the building block of customers presents a partly complete state. Although the owners of centralized PV plants are very typical and clear target customers, the companies to which they should sell the valuable materials recovered have yet to be determined, which is present in the future planning of most PV module recycling companies (NetEase, 2023b).

4.2.7 Innovation-specific institutions

In this building block, institutions refer to formal or informal policies, laws, and regulations. These institutions mainly describe the requirements for the product and its related production and services, or regulate how the actors should deal with the product and system around it (Ortt, 2022).

At present, China has not given clear instructions on PV module recycling at the legal level. However, in order to prepare for the coming wave of module recycling and to promote the development of PV module recycling in an industrial direction, a number of policies have been promulgated in recent years to point the way for PV module recycling. The names, contents, dates of promulgation, and agencies of the relevant policies are listed in Table 9.

Table 9: China's PV module recycling industry related policies

Policy Name	Content	Time of promulgation	Promulgating authority
Action Plan to Peak Carbon by 2030	It is pointed out that the recycling of retired PV modules should be promoted.	24-10-2021	The State Council
The implementation Plan on Accelerating the Comprehensive utilization of industrial resources	It clearly points out to promote the comprehensive utilization technology research and development and industrial application of waste PV modules.	27-01-2022	Eight departments, led by the Ministry of Industry and Information Technology
Circular on promoting the coordinated development of PV industry chain and supply chain	It mentioned the need to strengthen the whole life cycle management and carbon footprint accounting of the PV industry chain, and accelerate research on the recycling technology, standards and industrialization of discarded modules.	12-08-2022	The Ministry of Industry and Information Technology, the State Administration for Market Regulation and the National Energy Administration
Vigorously develop the new generation of information technology industry (Details mentioned in the press conference)	It calls for speeding up the revision and improvement of the PV standard system, and promoting the construction of public service platforms such as PV module recycling and carbon footprint verification.	20-09-2022	The Ministry of Industry and Information Technology

Guidelines on Promoting the development of energy Electronics Industry	It is further required to accelerate the construction of PV supply chain traceability system, emphasizing the promotion of PV module recycling technology research and development and industrial application.	03-01-2023	Six departments, led by the Ministry of Industry and Information Technology
Notice of China PV Industry Association on preparing to set up a PV module recycling working Group and collecting members of the working group	It is proposed to set up a PV module recycling working group to help the technological progress and industrial development of module recycling.	27-02-2023	China Photovoltaic Industry Association

In October 2021, The State Council put forward the action plan for achieving carbon peak before 2030, which clearly requires promoting the recycling of decommissioned PV modules (The State Council, 2021). Although this is the earliest mention of PV recycling policy in China, its content has not been specific. Details such as how to develop standards, how to promote research and innovation in recycling technology, and how to encourage companies to invest in PV module recycling, are not explained further. In January 2022, eight departments headed by the Ministry of Industry and Information Technology issued an implementation plan on accelerating the comprehensive utilization of industrial resources, which explicitly mentioned to promote the research and development and industrial application of the comprehensive utilization technology of waste PV modules (The State Council, 2022a). The document fills a gap in policy on research and development of waste PV module disposal technologies. In August of the same year, the Ministry of Industry and Information Technology, the State Administration of Market Regulation and the National Energy Administration jointly issued a notice on promoting the coordinated development of PV industry chain and supply chain, which clearly required to strengthen the whole life cycle management of PV industry chain and carbon footprint accounting, and accelerate the research on the recycling technology, standards and industrialization of discarded modules (MIIT, 2022a). On the basis of the original policy, it emphasizes the concept of industrial chain and the urgency of research on the recycling technology and standard of discarded modules. The following month, the Ministry of Industry and Information Technology held a series of press conferences on the theme of ‘Development of industry and information Technology in the New Era’, again emphasizing the need to accelerate the revision and improvement of the PV standard system, and promote the construction of public service platforms such as PV module recycling and carbon footprint verification (MIIT, 2022c).

There are still some policies related to PV module recycling released this year, but the main content is not much updated from the previous. In January 2023, six departments headed by the Ministry of Industry and Information Technology issued guidelines on promoting the development of energy electronics industry, which further emphasized and required the construction of PV supply chain traceability system, the promotion of PV module recycling technology research and development and industrial application (MIIT, 2022b). In February this year, China Photovoltaic Industry Association planned to set up a PV module recycling working group and solicited members. The main work contents of this working group include: 1. Track the work dynamics of PV module recycling at home and abroad, and analyze its development trend. 2. Cost analysis of PV module recycling and discussion of its business model. 3. Exchange and discuss PV module recycling technology. 4. Put forward relevant policy suggestions. 5. Cooperate with specified relevant standards (China Photovoltaic Industry Association, 2023). These work contents will be of great help to the enterprise's PV module recycling. On the one hand, companies can discuss advanced recycling technologies with the working group. On the other hand, the two can discuss the most appropriate business model based on the full analysis of recovery costs.

Looking at the existing policies on PV module recycling in China, it has a good role in promoting the research and development of PV recycling technology and the formation of the related industrial chain. For PV recycling companies, these policies are positive because they show that policymakers are paying increasing attention to the industry. On the other hand, they have convinced companies that developing competitive module recycling technologies is the key to their future presence in the PV module recycling market. However, the coverage of these policies is not comprehensive enough. As can be seen from Table 8, by February 2023, policies related to PV module recycling continue to encourage and require accelerated research and development of related technologies, industrial application and formulation of standards. These policy themes are not sufficient to constitute a complete policy system. There are a number of policy gaps that need to be filled: the first is whether companies need a special license to work in the PV module recycling industry (Insight And Info, 2023). Earlier in the recycling of lithium batteries, the Ministry of Industry and Information Technology adopted the way of issuing standard conditions and enumerating the white list. In other words, only when the enterprise meets the requirements of the standard conditions, it is eligible to enter the whitelist and obtain the qualification of recycling (NetEase, 2023b). This can greatly promote the competition between enterprises. It remains to be seen whether the same approach is appropriate for the PV module recycling industry. Second, and very important for PV module recycling enterprises, is whether the government will subsidize the parties engaged in PV module recycling, and how to subsidize them. At the 14th Environmental Protection Industry Forum organized by the China Academy of Environmental Protection Industry, experts introduced the current problem of poor economic efficiency of PV module recycling (China Environmental Protection Industry Research Institute, 2023). According to the study, the cost of recycling a standard-size PV module is about 1.3 times the total revenue. Although costs will be reduced in the future as the technology improves, government subsidies for PV recycling projects are necessary for now. The third point is whether it is necessary to formulate a policy to define the responsible body related to recycling. Where

PV module recycling itself is not economically beneficial and government subsidies are not provided, producer responsibility may need to be adopted, i.e., PV module manufacturers do the recycling themselves (Xinhua, 2023b). If a similar policy is implemented, it remains to be seen whether it is good or bad for PV recycling companies. For high-tech companies specializing in module recycling, module recycling is no longer a business, but they can cooperate with PV module manufacturers at the technical level to improve the economics of recycling and profit from the cooperation. For PV module manufacturers, recycling their modules has become a mandatory requirement. If the technical level is not improved, the disposal of a large number of waste modules will bring a large loss. But such policies offer opportunities if it works with multiple partners to improve the efficiency of recycling technologies and the economy of recycling processes.

Turning attention to China's standards for PV module recycling. At present, China has issued two relevant national standards, whose serial numbers, names and main contents are listed in Table 10.

The ‘General technical requirements of thin-film photovoltaic module recycling and reusing for use in building’, issued in June 2020 and implemented in April 2021, defines terms and definitions related to the recycling of modules, and sets standards for the collection, transportation, storage, disassembly, handling of modules, and recycling of materials (National Standard Full Text Disclosure System, 2020). This standard covers a wide range of topics, but the level of detail is not enough. In particular, there is no breakdown of the different processing techniques and the corresponding standards. The ‘General technology requirements for photovoltaic module recycling and recovery’ released in March 2021 was officially implemented in February 2022. Compared with the standards related to the recycling of PV modules issued last time, this standard specifies in more detail the recycling technology to be used for each part of the module and the emission requirements of related pollutants, and specifies in detail the recycling rate of each recycled material (National Standard Full Text Disclosure System, 2021).

Table 10: National standards related to photovoltaic module recycling

Standard number	Name	Main content
GB/T 38785-2020	General technical requirements of thin-film photovoltaic module recycling and reusing for use in building	1. Relevant terms and definitions are clarified. 2. Standards are established for the collection, transportation, storage, disassembly, handling of modules and recycling of materials (metals, glass and polymers).
GB/T 39753-2021	General technology requirements for photovoltaic (PV) module recycling and recovery	1. Relevant terms and definitions are clarified. 2. Standards are established for the collection, transportation, storage and disassembly of discarded PV modules. 3. Pollutant discharge standards are set for different recycling and treatment technologies. 4. The recycling methods of different components of the module (including photovoltaic laminates, glass, film, photovoltaic cells, metal belts, back sheets and frames, etc.) are defined, and the emission standards of related pollutants are established. 5. Regulations relating to the recycling of recovered materials (semiconductors, metals, glass and polymer materials, etc.) are provided.

The above two national standards well fill the gap in China's PV module recycling standards. However, they are not yet sufficient to constitute a complete standard system (China Business Journal, 2022). In terms of content, they belong to the general technical requirements standards. In order to establish a standard system, the standards involving PV modules to determine whether they are wasted are also essential. The introduction of such a standard will clarify which modules can be called waste modules and what the criteria are.

To sum up, the analysis shows that the building block ‘innovation-specific institutions’ is partially complete. In recent years, many policies have been promulgated to promote the research and development of PV module recycling technology and its industrial application, but the policy system is not complete. In particular, subsidies for PV recycling have not been introduced. On the other hand, although there are two common technical requirements standards, they are not sufficient to constitute a standard system. What is missing is the criterion for judging the waste modules. For PV recycling companies, the existing policies and standards are undoubtedly positive. They demonstrate the importance the government attaches to the PV module recycling industry and highlight the vast market in the future. However, subsidy policies are essential for companies to spread specific recycling technologies on a large scale in the future. The standard of waste module judgment will also play a guiding role in the research and development of related technologies. On the whole, the incompleteness of the building module mainly comes from the incompleteness of the policy and standard system.

4.3 Analysis of influencing conditions

4.3.1 Knowledge and awareness of technology

This influencing condition consists of two types of knowledge: the first is fundamental knowledge, which focuses on the technological principles of the components of TIS, such as products, production systems and complementary products. The second is applied knowledge, focusing on the development, production, maintenance and improvement of these TIS components (Ortt, 2022).

The fundamental knowledge will be analyzed first, focusing on the three components of TIS: products, production systems and complementary products. In this study, the product refers to the recycling of used PV modules, and the actors involved include large PV leading enterprises and high-tech enterprises specializing in PV module recycling. For these actors, mastering the fundamental knowledge is reflected in the enterprise's understanding of the various steps of recycling and the corresponding technical principles. In fact, according to the information that has been published, only two companies have the ability to build a complete PV module recycling demonstration line, respectively, Jinko Solar and Yingli Group (China Business Journal, 2022). They have built PV module recycling demonstration lines based on chemical and physical methods in Shangrao, Jiangxi and Baoding, Hebei respectively (Insight And Info, 2023). For other PV recycling companies, their status in the PV module recycling market tends to be 'advanced layout', that is, some companies announce research and development of efficient technologies in their planning, while others focus on a certain process of recycling, or research on efficient recycling of specific materials. Typical companies include DAS SOLAR, which is expending its PV recycling business (Insight And Info, 2023), and New Universal Science and Technology, which is focusing on the purification of silicon waste (Insight And Info, 2023).

In this study, the production system refers to the process of recycling waste PV modules into usable raw materials. The main actors involved in this process include: owners of centralized PV plants and PV module recycling enterprises. To build a production system, the first fundamental knowledge to master is how to judge that the PV module has been scrapped. At present, China has not issued relevant standards for this (China Business Journal, 2022), so the knowledge of actors in this area is missing. On the other hand, building production systems also means that actors have the ability to produce high-quality products on a large scale (Ortt, 2022). From this point of view, the actors are mainly Chinese PV recycling enterprises. As mentioned earlier, according to current information, only two companies have built PV recycling demonstration lines. For them, the knowledge to achieve the scale of PV module recycling is already mastered. Data show that the recycling demonstration line built by Yingli Group has an annual processing capacity of 10MW, and the recovery rate of silicon, silver, copper and other materials exceeds 90% (Insight And Info, 2023). The chemical recycling demonstration line built by Jinko Solar also has a similar treatment scale and recovery efficiency (Insight And Info, 2023). However, for other PV recycling companies, the basic knowledge to build production systems is missing. No matter how much technical optimization they can achieve in a certain part of the recycling, or how much development potential they have, in the final analysis, they do not have the ability to recycle PV modules at scale.

Regarding complementary products, the first is the periodic overhaul of PV modules.

Although the information currently available does not indicate that all actors, including centralized PV plants and PV recycling enterprises, can grasp the relevant technical principles, inspection can be done by a third party. These testing institutions usually have a wealth of experience and can ensure a rigorous attitude to regularly test the appearance, safety, performance and other indicators of PV modules (Interviewee A). In addition, some simple tests do not involve much expertise, considering that the cycle of checking modules is usually one year, or even less (NetEase, 2023b), it is also possible for PV module recycling enterprises to deepen their proficiency through a simple learning process. The second is the treatment of pollutants in the recycling process. Considering the significance of dealing with the pollutants generated by recycling only when it is discussed in the large-scale recycling of PV modules, the two enterprises that have built the PV module recycling industry demonstration line are still analyzed here. For the physics-based recycling demonstration line built by Yingli Group, the dismantling process of modules is green and environmentally friendly (Insight And Info, 2023), so the enterprise as an actor do not need to master the basic principles of pollutant treatment. For Jinko Solar, the recycling demonstration line built is based on chemical method, and pyrolysis method is the core of the treatment process (Insight And Info, 2023). There is no evidence that Jinko Solar has fully mastered the technology to thoroughly deal with contaminants. Therefore, the actor's basic knowledge in this area is incomplete.

In addition to the fundamental knowledge, whether actors have the applied knowledge will also be analyzed. The focus remains on the three components of TIS: products, production systems, and complementary products. As mentioned earlier, most PV recycling companies have not fully mastered the complete recycling technology, nor can they scale the recycling treatment. In the absence of this fundamental knowledge, it is impossible to master the applied knowledge. For the two companies that have built PV recycling demonstration lines, they also have only partial applied knowledge. Since Yingli Group and Jinko Solar have put industrial demonstration lines into use (Insight And Info, 2023), the companies have enough knowledge to complete the manufacturing and maintenance of products. However, it is unclear whether either company has the knowledge to improve their products. For the demonstration line built by Yingli Group on the basis of physical law, because the recycling process is green and pollution-free, and the metal recovery rate is high (Insight And Info, 2023), there is little room for improvement in environmental protection and effectiveness. The breakthrough point of technology is to expand the scale of production (NetEase, 2023b). For the demonstration line based on chemical method built by Jinko Solar, expanding the scale is also a product improvement direction. In addition, reducing the production of pollutants in the recycling process also requires relevant technological improvements (Insight And Info, 2023). Taken as a whole, these improved technical areas involve specific and specialized knowledge. This knowledge needs to be further acquired through research and development. Therefore, the two companies that built the recycling demonstration line do not yet have these applied knowledges. Regarding the maintenance of PV modules in complementary products, the third-party testing institutions have mastered the basic knowledge and have been professionally engaged in relevant testing items for a long time, including appearance inspection, scanning inspection, insulation inspection, module repairing, etc. (Interviewee A). This is a good indication that they have an applied knowledge of this complementary service. Another complementary product, the recovery of pollutants in the recycling process, should also be analyzed whether the relevant applicable technologies are available to the actors. As mentioned earlier, among the companies that have built the recycling demonstration line, only Jinko Solar needs to consider the problem of dealing with pollutants (Insight And Info, 2023). However, the company lacks the fundamental knowledge to deal with pollutants, let alone the practical knowledge to maintain and improve such complementary products.

Taken together, the influencing condition of knowledge and awareness of technology profoundly affects the building blocks of product performance and quality, production systems and complementary products and services. The incompleteness of fundamental and applied technologies has led to the current state of these building blocks.

4.3.2 Knowledge and awareness of application and market

This influencing condition refers to the knowledge of how and in what applications the technology is used. It also includes knowledge related to market structure and relevant actors (Ortt, 2022).

The analysis in this section begins with knowledge of how and in which applications the technology is used. As a product, the primary target customer for the recycling of waste PV modules is centralized PV power stations. For them, they have enough knowledge on how to apply the product. The PV power station pays the PV module recycling companies to obtain the related services of recycling (NetEase, 2023a). But from another point of view, centralized PV power plants lack sufficient knowledge in the purpose of applying products. This is mainly due to the peak of China's PV module retirement has not yet arrived (NetEase, 2023a), and only sporadic waste modules appear. However, there is an increasing demand for replacement modules in the Chinese PV industry, as the efficiency of today's modules is much higher than in 2010 (NetEase, 2023a). In this case, as one of the actors, the centralized PV power station has encountered a more awkward situation: whether to replace the new PV modules with higher efficiency, and regard the existing modules as scrap and seek recycling; Or wait a few years and seek centralized processing when the modules retirement time arrives.

For PV recycling companies, the application knowledge of the product is sufficient. Centralized power stations currently account for about 60% of China's total PV installed capacity (NetEase, 2023a), and they are put into use earlier and will be the first to usher in a wave of retirement. On the other hand, they are not yet able to accurately target the customer base of recycled raw materials and lack the application knowledge of raw materials. Still taking Jinko Solar as the object of analysis, according to the company's global solutions manager, the treatment of recycled silicon materials is a key project of the company's future focus, silicon materials will be used in the aluminum alloy industry, chemical industry and so on (NetEase, 2023a). But all of this is still very variable, because they have not yet been put into practice, and the downstream material demand enterprises are still unknown.

Another actor closely related to the application of technology is the demand business for recycled materials. It is envisaged that they buy products from PV recycling companies, that is, recycled raw materials, which are further processed for use in their respective industrial sectors (NetEase, 2023b). As a result, they know how to apply and what the product is for. However, the actual situation is highly uncertain. First, it is unclear where the raw materials go after they are recycled. The two companies that built the PV recycling demonstration line are still analyzed, and the information provided by them does not involve the whereabouts of these raw materials (Insight And Info, 2023). Secondly, in terms of the demand for raw materials, there is a large number of suppliers, and there are more than PV recycling companies to choose from. Their main business is already based on valuable materials, and after long-term cooperation with other suppliers, they have established good partnerships and will not be overly dependent on PV recycling enterprises. The raw materials provided by PV recycling companies only add a supplier choice for these companies. Take glass as an example, affected by COVID-19 pandemic, China's glass industry has a long inventory backlog (Sina Finance, 2022a). Nowadays, with the recovery of glass demand, destocking has become the general direction of change in the industry. In this case, due to the large amount of glass inventory, traders will take price, quality and other as the main judgment criteria to select glass products from the inventory (Sina Finance, 2022a). Therefore, for the raw materials provided by PV recycling companies, whether they are attractive enough at the price and quality level is still a big unknown.

In addition, as a member of the actors, the supplier of recycling equipment and chemical reagents is also important for large-scale recycling treatment. At present, it is not clear whether the two PV recycling demonstration lines that have been built have their own recycling equipment developed or jointly developed with equipment suppliers (Insight And Info, 2023). However, chemical reagents must be provided by relevant chemical enterprises. Whether the actors in the network have knowledge of application is uncertain. On the one hand, it is not clear whether the supplier of the recycling equipment understands the whole recycling process, and on the other hand, whether the supplier of the chemical reagents understands how the reagents will be applied remains to be proven. From this point of view, the lack of relevant application knowledge hardly seems to have a positive impact on the formation and coordination of the network.

The second part of this subsection is an analysis of whether the actors have sufficient knowledge and awareness of the market structure and relevant participants. For centralized PV plants, as both actors and customers, they know which companies can provide PV module recycling products. Since centralized PV power plants are mainly held by state-owned enterprises and belong to state-owned assets (NetEase, 2023a), PV recycling companies are carefully considered when officially decommissioned to ensure that state-owned assets are not lost (NetEase, 2023a). When analyzing PV recycling companies, the picture is relatively complicated. For one thing, they don't know enough about market participants. This is mainly reflected in the fact that they do not fully consider the demand for recycled materials. As mentioned above, Jinko Solar regards the development of this business as the goal of future efforts (NetEase, 2023b), but at this stage, the potential market participants can only be classified in a general way, for example, the demand for silicon materials is related to the aluminum alloy industry and the chemical industry (NetEase, 2023b). On the other hand, they also lack an understanding of market structure. After seeing that the PV recycling market has development prospects, the participants have become more and more. According to the general manager of Nantong Riyi New Environmental Protection Technology Co., LTD., the addition of some "small workshops" has led to market chaos (NetEase, 2023a). They are all small and micro enterprises and self-employed people who gain profits by reselling used PV modules (NetEase, 2023b). In this case, it is difficult for regular PV recycling companies to accurately grasp the market structure, because the number of waste modules currently obtained by these small and micro enterprises and self-employed people and their proportion of the entire market cannot be known. For companies that need recycled materials, the market structure is clear. As previously analyzed, these companies are not relying on raw materials provided by PV recycling companies (Sina Finance, 2022a). They have built trusting relationships with other suppliers and have a good understanding of the market they operate in. Who are the suppliers, the quality of the products and the price are all in their hands (Sina Finance, 2022b). However, these companies do not know enough about PV recycling companies. In the case that they have long-term partners, it is difficult to arouse their interest if PV recycling companies are not attractive enough as latecomers. And the vast majority of PV recycling companies do not announce the quality and price of their recycled materials and other information, it is difficult to let people have a sufficient understanding of it (China Business Journal, 2022).

On the whole, the influencing condition of knowledge and awareness of application and market involves multiple actors such as PV recycling enterprises, centralized PV power plants and downstream recycling materials demand enterprises. It will have an impact on three modules: product price, network formation and coordination, and customer. The detailed relationship between them is described in section 4.4.

4.3.3 Natural, human and financial resources

This influencing condition concerns the availability of resources. Resources are divided into three categories, first natural resources, then human resources, and finally financial resources. Lack of these resources will hinder the formation of TIS (Ortt, 2022).

First, the creation of products, production systems and complementary products does not involve all types of energy. According to the classification of PV module recycling technologies in Chapter 3 of this paper, water does not seem to be a necessity for any of them. However, land resources are the key to creating products and production systems. For PV recycling enterprises, the demand for land resources comes from the construction of recycling bases or recycling plants. Taking the two PV module green recycling processing demonstration lines built in China as the object of analysis, although they do not have a specific floor area to query, considering their module recycling capacity of more than 10MW (Insight And Info, 2023), sufficient land resources are needed to achieve it. According to Yingli Energy's layout, the physics-based recycling demonstration line is located in the PV intelligent manufacturing production demonstration base established by the company in Li County, Baoding City, Hebei Province, China (Xinhua, 2023a). As the area is far from the urban area, land resources do not incur high costs. It is a similar story for Jinko Solar's recycling demonstration line in Shangrao, Jiangxi Province (Insight And Info, 2023). Building a PV module recycling base in a relatively remote place can effectively use land resources and reduce product costs. In summary, land resources do not seem to be an obstacle to the large-scale diffusion of products.

Secondly, the mobilization of human resources is also available. At present, the completed recycling demonstration line cannot achieve full automation (Xinhua, 2023a), and human resources need to be mobilized to complete some auxiliary work in the recycling process. According to Yingli Energy, once the company's smart PV base is completed, more than 900 jobs will be added (Xinhua, 2023a). Although this figure does not only include the workers who assist with the recycling, it is still significant. On the other hand, the PV module recycling demonstration line has clarified the various steps (Xinhua, 2023a). It is foreseeable that the personnel who assist in the recycling work do not need to master advanced knowledge, they can learn the work content in a short time, and improve their proficiency after a period of practice. In general, human resource is not a hindrance in the creation of products, production systems and complementary products, it is easy to get.

Third, financial resources also play an important role in the creation of products, production systems and complementary products. Unfortunately, PV module recycling projects are completely unattractive in terms of cost performance. According to the analysis of technicians at the Institute of Electrical Industry of the Chinese Academy of Sciences, the current cost performance of component recycling is very low (NetEase, 2023b), and only when the technology is significantly improved (using as few chemicals as possible and producing as few pollutants as possible), the situation can be alleviated (NetEase, 2023b). Companies engaged in the recycling of PV modules have more profound feelings. The waste PV module recycling project of Nantong Riyi New Environmental Protection Technology Co., Ltd. has not achieved any profit since it was put into operation (NetEase, 2023a). Since the profits of regular enterprises to recover PV modules are difficult to cover transportation, dismantling and recycling, environmental protection and other related costs, the economy is not ideal. It is estimated that the loss is about 10% per recovered module (NetEase, 2023a). Coupled with today's chaotic PV recycling market, the existence of small workshops has seriously affected the healthy competition in the market. The combination of these factors creates significant difficulties in the use of financial resources. Considering that the government has not yet introduced subsidy policies, more and more PV recycling investors are in a wait-and-see state (NetEase, 2023a). Especially for high-tech enterprises specializing in PV recycling, the current market environment is very unfriendly, and once invested, it will not be unexpected to face losses. The situation of leading PV companies is slightly better, they can stand trial and error, but they are still waiting for the opportunity (NetEase, 2023a). In general, there are significant difficulties in mobilizing financial resources to support the creation of products, production systems and complementary products.

To sum up, the influencing condition of natural, human and financial resources is partially complete. The actors, led by PV recycling companies, have sufficient natural and human resources to create products, but the lack of sufficient financial resources to invest is a huge problem. This influencing condition can also explain the limitations of the building blocks of ‘product performance and quality’ and ‘production system’.

4.3.4 Competition

In this influence condition, competition mainly includes: competition between new technology and old technology innovation, competition between different product versions. When competing alternatives form alternative networks, the pattern of competition becomes chaotic and complex, directly impeding the formation of TIS (Ortt, 2022).

At this stage, PV module recycling technologies have not gone through the process of multiple improvements, so multiple product versions do not exist. In fact, even the two PV recycling demonstration lines built by Yingli Group and Jinko Solar have not experienced many technological updates. Considering that in March 2023, the two PV recycling demonstration lines were built (Insight And Info, 2023), and the time it has been put into use is not long, it is difficult for them to make technical breakthroughs in a short time.

However, the entry of new actors into the market has created a different kind of competition. These actors are known in the industry as ‘small workshops’, they are often small and micro enterprises or self-employed, playing the role of waste PV module buyers (NetEase, 2023a). According to the general manager of Nantong Riyi New

Environmental Protection Technology Co., LTD., small workshops have seen profits and collectively flooded into the PV module recycling market, leading to the current chaotic situation. There are two main reasons for this chaos. First, the rules of the market have changed. Before 2021, PV power stations paid PV recycling companies to dispose of waste PV modules for environmental protection (NetEase, 2023a). However, the situation changed after many actors joined in. After entering 2021, PV recycling companies need to first acquire waste modules before processing, that is, they pay for PV power stations (NetEase, 2023a). This is actually a very irrational way to trade (Interviewee A). From a practitioner's point of view, the recycling of PV modules themselves is difficult, the waste is not good to deal with, and the centralized PV power station should pay for the module recycling enterprises (Interviewee A). The recycling cost performance of some materials in the modules is very low (Interviewee A), when the recycling enterprise purchases the waste modules at a certain price, plus the cost of recycling and disposing of waste, it will be higher than the value of the recovered materials. In this case, module recycling faces an inevitable loss.

The second is the chaos in the PV recycling market. The entry of small workshops into the market does not bring healthy competition. Since they are not strictly recycling PV modules, there is no need to consider environmental issues, they only do simple disassembly, landfill, incineration and other ways to dispose of the modules (NetEase, 2023a). In this case, the competitiveness of the products provided by formal PV recycling enterprises is greatly reduced. For them, in order to ensure a certain number of profits, the purchase price of waste PV modules cannot be given too high. And small workshops seize this, hoarding waste PV modules, bid up the purchase price (NetEase, 2023a). In this way, healthy competition in the industry is destroyed.

In addition to the competition with small workshops, the competition between regular PV module recycling enterprises is not fierce, and even can be ignored. It is mainly caused by the following two reasons: First, there are not many enterprises that can truly provide complete and large-scale PV module recycling, and they are worried about high trial and error costs (NetEase, 2023a), so even if they have equipment and technology, they do not formally enter the market to compete. The second reason is that the poor economy has led to the insufficient development momentum of the PV recycling market. Because of the lack of subsidy policies and mandatory requirements (NetEase, 2023a), companies have insufficient motivation for research and development, and the willingness to occupy the market is not strong, after all, the current PV recycling business seems to be 'steady loss'

(NetEase, 2023a). In this case, the competition between PV module recycling companies can be negligible. Companies do not worry about the impact of technology version lag on their position in the market; There is also no incentive to expand competitive advantage by improving the performance and quality of products.

To sum up, competition has a great impact on the building block of product performance and quality and product price. After the influx of small workshops into the PV module recycling market, the purchase price of PV modules has been raised, and the corresponding recovery cost for PV recycling enterprises has also increased. This is helpful in explaining the partial completeness of the building block of product price. In addition, the lack of competition among formal PV module recycling companies also explains why not all companies can provide products that ensure performance and quality.

4.3.5 Macro-economic and strategic aspects

In this influencing condition, macro-economic conditions refer to economic recession or growth, which will hinder and promote TIS, respectively. The conditions involved, such as market structure and mode of operation, usually reflect the country's strategic policies in important industries. The combination of these conditions can have an impact on TIS building blocks (Ortt, 2022).

According to the data, China's annual GDP in 2021 and 2022 increased by 8.1% (The State Council, 2022b) and 3.0% (The State Council, 2023), respectively, compared with the previous year. As the Chinese economy has been repeatedly affected by COVID-19 throughout 2022, the economic growth rate in 2021 has declined significantly. However, according to the report, solar cell production reached 340 million kilowatts, an increase of 46.8% year-on-year (The State Council, 2023), which is undoubtedly a very considerable number. In the case of the worsening economic environment and the great original base, China's PV industry is still developing rapidly, fully reflecting its popularity. Behind the huge PV market, there is also a sizeable PV module recycling market. Although there is no direct evidence that the structure of the PV recycling market and the way of doing business are too much affected by macro-economic growth, the construction of the PV green industry chain is mentioned many times by the state, which is also an important strategic policy in the field of PV module recycling. Considering that by the end of 2022, China has fully lifted its COVID-19 prevention and control measures (The State Council, 2022c), it is foreseeable that the impact of COVID-19 on the Chinese economy will be greatly reduced. In this case, the country's policy focus will return to important industries. PV module recycling, as the last part of the PV green industry chain, will also be valued.

To sum up, macro-economic and strategic aspects have an impact on the building block of innovation-specific institutions. Macro-economic growth has slowed due to the impact of COVID-19, and China has had to shift its policy focus to economic recovery in 2022, which partly explains why the building block of innovation-specific institutions is partially complete.

4.3.6 Socio-cultural aspects

The influencing condition refers mainly to the norms and values held by important actors in the socio-technical system, which may not be formal, but have an impact on the formation of institutions and the behavior of actors in TIS (Ortt, 2022).

At present, China's waste PV module recycling market is in a relatively chaotic period. The main reason for this situation is the influx of small workshops selling waste PV modules into the market, resulting in vicious competition (NetEase, 2023a). The values held by these small workshops are mercenary. In fact, their treatment of waste PV modules cannot be called ‘recycling’, because they only do simple disassembly of waste modules, and the remaining parts that cannot be disassembled are directly doped in domestic waste incineration (NetEase, 2023a). These small workshops that resell waste PV modules only want to benefit, while ignoring environmental factors, strictly speaking, cannot be called stakeholders, but it is a real actor in the PV recycling industry, and they are constantly changing the gathering place (NetEase, 2023a). Since there is no need to consider the environmental treatment of waste modules, these intermediaries charge modules at 20% or more above the market price. This behavior has seriously affected the healthy competition in the PV recycling industry, which directly leads to the increase in product costs of regular PV recycling enterprises, and the lack of sufficient waste modules for batch processing and technical optimization (NetEase, 2023a). In general, the incorrect value of the newly influx of actors in the PV recycling market is a major hindrance.

The second point, which is also the value of many actors in the PV module recycling industry, is to adopt a conservative attitude in the face of uncertainty. Since the state has not yet issued a clear subsidy policy, there are no mandatory requirements, in the face of the PV module recycling market with little profit and insufficient development power, there are few enterprises that really invest a lot of money to organize the large-scale recovery of PV modules (NetEase, 2023a). According to the director of the Zero Carbon Institute, there are only a few companies that are doing well, and they all have their own recycling equipment. However, none of them have put their recycling lines into production (NetEase, 2023a). In essence, the high cost of trial and error and the inherent conservative psychology of enterprises lead to this situation.

In summary, the new influx of small workshops into the market with mercenary values, disrupting the normal market order, is a prominent obstacle. From this point of view, this influencing condition goes a long way in explaining the partial integrity of the building blocks of product price, because the chaotic market order leads to higher costs for formal PV module recyclers and insufficient funds to improve the technology. On the other hand, conservative attitudes make companies reluctant to put recycling lines into large-scale use, which can also explain part of the integrity of the building block of the production system.

4.3.7 Accidents and events

In this influencing condition, an accident may refer to a production accident or a product failure accident. In addition to these accidents that occur within TIS, it also refers to external accidents such as wars and natural disasters. Both types of accidents can have an impact on the components of TIS (Ortt, 2022).

The first thing to analyze is the internal accident in TIS. For now, there have been no major production accidents on China’s PV recycling demonstration line. Due to the exemplary role of the demonstration line itself, enterprises pay more attention to various recycling links, and the equipment in the recycling demonstration line has not been put into use for a long time (Xinhua, 2023a), so there is no such accident as product failure. In terms of external incidents, they are mainly related to the COVID-19 pandemic and the Russia-Ukraine war. Before China lifted its coronavirus ban, production was rarely halted outright. With China fully liberalizing its novel coronavirus prevention and control measures by the end of 2022 (The State Council, 2022c), the impact of the novel coronavirus on the PV recycling industry was minimal. In addition, although the Russian-Ukrainian war has significantly affected energy prices, it has little impact on the Chinese PV market. Some Western countries have increased their attention to renewable energy after this incident, but this has not happened in China. The state is still in accordance with the original schedule layout of the PV industry. In this case, the impact on PV recycling is minimal.

In general, accidents and events have no influence on each TIS building block in this study.

4.4 Relationship between each influencing condition and building blocks

This section describes the relationships between the influencing conditions and the TIS building blocks in the following order: First, a diagram of the relationships is given, their specific contents are described, and then the reasons for the formation of these relationships are analyzed.

Figure 9 shows the relationship between each influencing condition and each building block. Where red modules indicate that the influencing condition or TIS building block is incomplete or incompatible; Yellow modules indicate that the influencing condition or building block is partially complete or partially compatible; Grey modules indicate that the influencing condition does not affect any building blocks in this study. As can be seen in the figure, the influencing condition of the accidents and events does not affect any building blocks; The blue arrows indicate which building blocks are affected or caused by the influencing conditions. The influencing condition 'knowledge and awareness of technology' affects three different building blocks: product performance and quality, production system and complementary products and services. Most PV module recycling companies only master some of the basic knowledge related to technology, and have not yet mastered the applied knowledge to improve products, resulting in their inability to ensure the performance and quality of products to meet the needs of target customers. At the same time, only a small number of companies (Led by Yingli Group and Jinko Solar) have the basic knowledge related to the production system, they can scale recycling, but compared to the number of used PV modules in the future, the scale of these recycling is still very small. (Science Net, 2022). And they don't yet have the knowledge to continuously expand the scale, since the related technology has yet to be developed. In addition, there is no evidence that PV module recyclers in China have the knowledge related to complementary products and services, especially the treatment of pollutants generated during the recycling process. This results in a partial completion of the building block of complementary products and services.

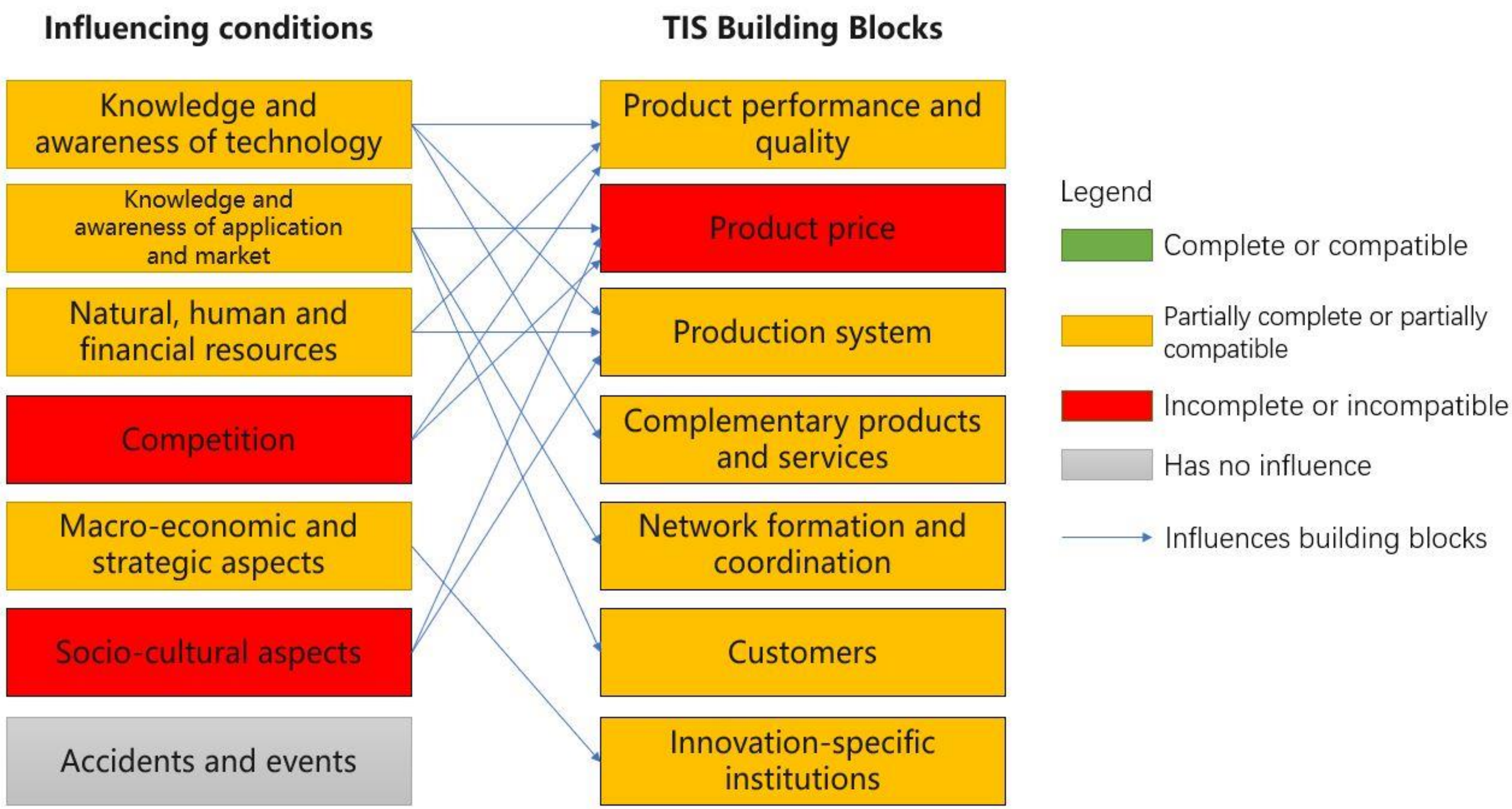

Figure 9: The relationship between influencing conditions and building blocks of PV module recycling in China

Knowledge and awareness of application and market also affects three building blocks: product price, network formation and coordination and customers. First of all, PV module recycling companies have a lack of awareness of the current relatively chaotic market structure, although this is not their fault. The new influx of small workshops has destroyed the market order and seriously increased the production costs of these enterprises (NetEase, 2023a). This explains why the building block of product price is incompatible. At the same time, enterprises that have a demand for recycled materials, as target customers, lack awareness of products. This is mainly due to the fact that PV module recycling companies are selling materials as part of their future business (NetEase, 2023b) and have not yet published specific information about their products, including the purity of the materials provided, the selling price, etc. And since the target customers have long-term cooperation and reliable relationship with material suppliers, PV recycling companies are difficult to enter their attention. The above reasons lead the building block of customer being partly complete. In addition, the lack of application knowledge of some of the actors in the network, especially recycling equipment suppliers and chemical reagent suppliers, leads to the partial completeness of the building block of network formation and coordination.

The influence condition of natural, human and financial resources is partially complete. Among them, there are no barriers to the use of natural and human resources by PV recycling companies. However, the lack of adequate financial resources is a major problem. As a result, most companies in the PV module recycling industry lack funds for technology development and upgrading to ensure product performance and quality. There is also insufficient funding for research into the conditions required for large-scale recycling.

The influencing condition of competition is incompatible with the large-scale diffusion of products. On the one hand, the current chaotic market order is seriously lacking in legitimate competition, and the existence of small workshops has led to an increase in the cost of formal PV module recycling enterprises, which has led to the incompatibility of the building block of product price. On the other hand, formal PV recycling enterprises do not have enough research and development power, their economic benefits are not good, and there is a lack of competition between each other. Therefore, it is not realistic for enterprises to continuously improve product performance and quality in exchange for competitiveness. This also results in a partial completeness of the building blocks of product performance and quality.

The influencing conditions of macro-economic and strategic aspects affects the building block of innovation-specific institutions. Affected by recurrent COVID-19 outbreaks, China's economic growth rate for the whole year of 2022 is significantly lower than that of the previous year. The country's policy focus is on economic restart and recovery (The World Bank, 2022). In this case, the development of policies and standards for the recycling of PV modules is lagging behind. This also explains why the current building block of innovation-specific institutions is partly complete.

Socio-cultural aspects mainly affect two building blocks: product price and production system. First of all, the small workshops pouring into the PV module recycling market hold a mercenary value and bid up the price of module recycling, resulting in the high cost of regular PV module recycling companies, which brings obstacles to large-scale diffusion. This helps explain the incompatibility of the building block of product price. In addition, the conservative attitude of most recycling companies makes them afraid to conduct large-scale recycling research and experiments, resulting in no impressive breakthroughs in this area. This also helps explain the partial completeness of the building block of production system.

5. Strategies for large-scale diffusion of waste PV module recycling in China

In order to enable the recycling of used PV modules to diffuse on a large scale in China, appropriate niche introduction strategies are specified in this chapter, and information on their respective types, scope and timing is provided. When analyzing each niche introduction strategy, the following sequence is used: First, the name of the niche strategy is indicated. Then describe its specific content, including the type, the actors involved, the introduction time, and so on. Finally, what barriers the niche strategy can address are pointed out. These barriers, which affect the large-scale diffusion of PV module recycling, are caused by incomplete or partially complete building blocks and influencing conditions. It should be pointed out that the theories about niche strategies in this chapter are based on the ten niche strategies proposed by Ortt, et al. (2013) to commercialize high-tech products. In addition, some important policies and standards, including how to incentivize investment, how to regulate the market, and what standards to judge the waste of PV modules, are crucial to the healthy development of China's PV module recycling industry at this stage. And they often cannot be unfolded from a corporate perspective. Therefore, the second half of this chapter focuses on analyzing potential strategies from the perspective of policy makers and standard setters.

The main structure of this chapter is as follows: section 5.1 lists niche introduction strategies that address barriers due to deficiencies in building blocks and influencing conditions. Information about the type, time, size, etc. associated with the niche strategies is also specified. Section 5.2, from the perspective of policy makers and standard setters, analyzes strategies that can be adopted to address the issues that hinder the large-scale diffusion of PV recycling in China. Finally, section 5.3 is a reflection on the whole chapter.

The last sub-question is answered in this chapter, namely:

Sub-question 6: What strategies could be adopted to enable large scale diffusion of waste silicon PV module recycling technologies in China?

5.1 Niche introduction strategies for PV module recycling in China

5.1.1 Demo, experiment and develop niche strategy

The first part of this niche strategy is that PV module recycling companies regularly demonstrate product quality to companies in demand for recycled materials. The products here refer to the valuable materials such as silicon, aluminum and silver that are recovered. One way to display can be to invite these target customers by PV leading enterprises to visit the company's exhibition hall. The other way is to be led by social organizations with greater influence in the PV industry, such as the PV Committee of the China Green Supply Chain Alliance, to select the exhibition location. In the exhibition, high-tech enterprises specializing in PV recycling and PV leading enterprises show the high quality and price advantages of the recycled materials they have processed. The target customers, that is, the companies that need these materials, are invited to visit the exhibition to learn about the characteristics of these products while contacting more PV module recycling companies. It is worth pointing out that the introduction of this niche strategy of ‘demo’ should take place after PV module recycling companies have fully developed the business of recycling materials for re-sale. In other words, at this stage, the company has been able to ensure the purity of the recycled materials and relatively low prices. This niche strategy can effectively solve the problem that the target customers have insufficient understanding of the enterprise and the product, and the corresponding influencing conditions and building blocks are knowledge and awareness of application and market and customers, respectively.

The second part of this niche strategy focuses on experimenting and developing the product. In the case of this study, the module recycling service provided by the PV module recycling company can be experimented. As mentioned earlier, the leading PV companies themselves, as PV module producers, undertook the construction of some centralized PV power stations. Product trials can be conducted around these PV power stations. By agreement between the two sides of the action, the centralized PV power station provides a part of the waste modules for PV enterprises to conduct experiments. With sufficient sources of waste modules, PV module recycling enterprises can carry out research more smoothly. After a certain period of time, PV module recycling enterprises have further developed and improved their products, and the treatment of high-quality products, large-scale production and recycling of pollutants has been guaranteed. On this basis, the two sides can further carry out in-depth cooperation. The introduction of this part of the niche strategy is, in principle, as soon as possible. Considering that the waste modules that can be studied are difficult to obtain and the number is small (Xinhua, 2023b), the introduction of this part of the niche strategy can enable PV module recycling enterprises to obtain basic and application-oriented knowledge related to product performance, production systems and complementary products. In addition, the influencing condition associated with this part of the niche strategy is knowledge and awareness of technology, and the relevant building blocks include: product performance and quality, production systems, and complementary products and services.

5.1.2 Subsidized niche strategy

In this niche strategy, it is the government that provides subsidies. For centralized PV power plants, obtaining high-quality and large-scale module recycling as soon as possible can effectively cope with the upcoming peak of PV module retirement. However, from the perspective of PV module recycling companies, on the one hand, the research and development of recycling technologies with high recovery rates and low pollution requires a lot of financial resources. On the other hand, the economic benefit of PV recycling at this stage is very poor, and the PV panels recovered per unit area are in a state of inevitable loss. Based on this situation, the government should provide adequate subsidies for PV module recycling enterprises. Subsidies can be divided into two categories: the first category is subsidies for technology research and development. The technologies involved here include: module recycling technology, scale treatment technology and pollutant treatment technology. Research and development subsidies can show the government’s importance to the relevant technology, and can also encourage PV module recycling companies to focus on research and development. The second category of subsidies is designed to reduce costs for companies that recycle PV modules. The government can specify how much subsidy it provides for PV modules per unit area. Considering the current situation of 10% loss on recycling a PV panel (NetEase, 2023a), providing subsidies here can release the economic pressure on PV module recycling companies and increase their incentive to carry out related business.

It should be pointed out that there are many government departments related to the PV industry in China, but the National Energy Administration and the Ministry of Industry and Information Technology are the most important two. Details on how to subsidize and the amount still need to be discussed jointly with other departments. The sooner this niche strategy is introduced, the better. At present, the PV recycling industry is in its infancy (NetEase, 2023b), and many PV recycling enterprises are in a difficult period due to insufficient access to financial resources. Government subsidies can effectively deal with the barriers brought about by the poor economy of PV recycling and high research and development costs for large-scale diffusion. The influencing condition involved in this niche strategy is natural, human and financial resources, and the building blocks involved include: product performance and quality, product price, production systems, and complementary products and services.

5.1.3 Educate niche strategy

This niche strategy has three parts. The first part is that PV module recycling companies hold regular seminars to educate potential investors in order to increase their knowledge about PV recycling technologies and the market, prompting them to make the right decision. As mentioned in the analysis of the influencing condition of ‘natural, human and financial resources’, there is a serious lack of financial resources for PV module recycling companies. This prevents module recycling companies from gaining further knowledge to improve product performance and build production systems. This niche strategy could be introduced as soon as possible to increase access to financial resources. Although it seems that PV module recycling is economically poor at the current stage and it is difficult to attract investment, if PV module recycling companies fully explain their development potential at the seminar, potential investors will be able to make the right decision. It is worth mentioning that this part of the niche strategy needs to complement the government's policy on stimulating investment in PV module recycling. The relevant policies that the government can make are analyzed in section 5.2. The influencing condition associated with this part of the niche strategy is natural, human, and financial resources, and the relevant building blocks are product performance and quality and production systems.

The second part of the education niche strategy is that PV module recycling companies can educate target customers who need to use materials such as aluminum, silicon, and silver. Education can still take the form of seminars. This niche strategy needs to be introduced when module recycling companies have mature technologies in the disposal of recycled materials. As mentioned earlier, for companies that need materials such as aluminum, silicon and silver, they usually already have long-standing and well-connected material suppliers. On the one hand, they lack sufficient understanding of the recycled materials that PV module recycling companies can provide, and do not know the purity, price and other key data of these materials. On the other hand, it is difficult for them to have the willingness to cooperate with module recycling companies. The development of the seminar gives the module recycling companies the opportunity to conduct in-depth education on the target customers, let them understand the purity of the materials provided by the company, price and other specific information, in order to look forward to further cooperation. This part of the niche strategy is expected to make enterprises in the stakeholder map with demand for recycled materials become real actors. The relevant influencing conditions are knowledge and awareness of technology, knowledge and awareness of application and market. The relevant building block is customers.

The third part of this niche strategy is for PV module recycling companies to hold meetings to impart knowledge about the module recycling process and treatment methods to recycling equipment suppliers and chemical reagent suppliers. This part of the niche strategy needs to be introduced at this stage. As previously analyzed, these suppliers have little knowledge of the module recycling process, and they do not know what role the recycling equipment and chemicals play. By organizing meetings, knowledge related to PV module recycling technology and recycling process can be passed on to suppliers. In this case, collaboration between suppliers will be easier to develop. Recycling equipment suppliers can understand the core steps of recycling to improve equipment performance; Chemical reagent suppliers can also improve in specific aspects for the specific use of reagents in the recycling process. Therefore, this niche strategy not only makes the suppliers of recycling equipment and chemical reagents in the stakeholder map become real actors, but also promotes the formation and coordination of the network to a certain extent. In summary, this part of the niche strategy is related to knowledge and awareness of technology, and the related building blocks are network formation and coordination.

5.1.4 Collaboration niche strategy

This niche strategy means that PV module recycling companies can cooperate with universities and scientific research institutions to share advanced module recycling technologies and create research and development projects to jointly improve product performance and quality. In fact, some PV module recycling companies have adopted this niche strategy. Taking Changzhou Ruisai Environmental Protection Technology Co., LTD as an example, they have jointly established Jiangsu Province retired PV module resource utilization engineering research center with Changzhou Institute of Technology and some other units, and have close industry-university-research cooperation with Nanjing University of Aeronautics and Astronautics and Changzhou University (Ruisai Environmental Protection, 2023c). This academic and research and development cooperation, on the one hand, is conducive to the development and dissemination of PV recycling technology, on the other hand, module recycling companies can rely on these cooperation platforms to further improve product quality. For example, the laboratories of partner universities can be used to carry out special upgrading of PV recycling products. Taken together, this niche strategy can address the obstacles caused by the partial completeness of the influencing conditions of knowledge and awareness of technology and the building block of product performance and quality.

5.1.5 Geographic niche strategy

This niche strategy means that PV module recycling companies can set up recycling test sites nearby in northwest China, and these test sites are small-scale. As previously analyzed, China's centralized PV power plants are mostly distributed in more remote areas in the northwest, where the cost of using land resources is relatively low. Although the analysis shows that there are no barriers to the use of land resources, lower costs are expected to contribute to the reduction of total costs, alleviating barriers caused by incompatibilities such as product prices. On the other hand, when the recycling point is built near a centralized PV power station, the opportunity for these target customers to understand the product is greater, and the shorter distance also reduces the transportation cost of used modules. Centralized PV power plants can send a small part of the waste modules to the PV recycling test site, after viewing the recycling effect, to make further decisions. In this case, the unfavorable market competition environment can be alleviated. At present, centralized PV power plants seem to focus only on price (NetEase, 2023a), which gives small workshops an opportunity to take advantage of. The situation is expected to improve as they learn more about the quality of the products. It should be pointed out that the chaotic order of the market and the unhealthy competition mechanism are far from enough by the introduction of this niche strategy, and also need the intervention of policy makers and standard setters, which is analyzed in the next section. This niche strategy can be introduced at the current stage to deal with barriers due to the incompleteness and patrial completeness of influencing conditions: competition and natural, human and financial resources, as well as building blocks: product prices and customers.

5.1.6 Top niche strategy

This niche strategy means that PV module recycling companies can provide high-quality products to the top customers. According to the previous analysis, the building block of the production system is partially complete, limited by capital, technology, and so on, almost no enterprise can build a production system. In this case, the module recycling company can target specific customers to provide them with small scale, but very high-quality PV module recycling services. These top customers can be centralized PV power plants managed by state-owned enterprises. In order to set a good example for other centralized PV plants, these top niche customers need module recycling services with high material recovery rates and effective pollutant treatment. In this case, providing them with high-quality products on a small scale can precisely meet their needs. The introduction of this niche strategy can be done after PV module recycling companies have mastered advanced pollutant treatment technology. On the other hand, due to the small scale of this high-end module recycling service, the cost of input will not be too high, and the conservative attitude of module recycling enterprises can be alleviated. They can try it out and compare the results before making further decisions. This niche strategy mitigates, to a certain extent, the barriers caused by the incompleteness and partial completeness of influencing condition: socio-cultural aspects, and the building block: production system.

5.2 Recommendations for strategies that policy makers and standard setters can adopt

The niche introduction strategies presented in section 5.1 address barriers arising from the incompleteness or partial completeness of different building blocks and influencing conditions. However, among the many partly complete influencing conditions, macro-economic and strategic aspects is not mentioned, and there are no corresponding niche strategies related to the building block it affects: innovation-specific institutions. This is mainly because these influencing conditions and building blocks are closely related to policymakers and standard-setters. The niche strategies in section 5.1 are mostly developed from an enterprise perspective. It is worth mentioning that given the current situation of the PV module recycling industry and market in China, the development of specific policies and standards is very critical. Market disruptions must be addressed by the government; Some missing policies and standards have also largely limited the large-scale spread of PV recycling. This section aims to outline strategies that can be adopted from the perspective of policy makers and standard setters to address the current situation.

5.2.1 Proposed policy strategies for policy makers:

① Develop policies to regulate the PV module recycling market

As previously shown, small workshops poured into the PV module recycling market, bid up prices, hoard used modules and other behaviors seriously disrupted the market order and destroyed fair competition. In order to maintain market order, it is necessary for the State Administration for Market Regulation to formulate corresponding policies. The department is responsible for the comprehensive management of the market, the formulation of corresponding policies and provisions, and the organization and guidance of market supervision and law enforcement (State Administration for Market Regulation, 2023). First, in order to severely crack down on hoarding, reselling of used modules and price gouging, penalties can be formulated. Second, there is a need to regulate the recycling process and formulate penalties, especially for the treatment of pollutants, and crack down on small workshops when they do not follow the prescribed process or adopt recycling methods that seriously pollute the environment. Third, when more detailed recycling standards are developed, the recycling quality of PV module recycling enterprises can be regularly assessed. Companies that have performed well in successive assessments are whitelisted and their products and services are officially certified. And for enterprises that perform poorly in the evaluation, they are ordered to make corrections.

② Formulate policies to encourage investment

Policies to stimulate investment need to be rolled out in parallel with subsidies. Typically, the National Energy Administration sets the overall policy, while local governments implement it with a degree of freedom. Taking the investment subsidies for distributed PV as an example, Zhejiang, Chongqing and other places respectively have carried out different degrees of subsidies for distributed PV projects, but the basic process is: issue detailed policies to explain the capital subsidies for investors per unit of power generation (Sohu, 2023). A similar approach can be taken for PV module recycling. First, the National Energy Administration issued a general policy on promoting investment in PV module recycling, and then implemented by the regions. The policy issued by the region can be precise to how much money is subsidized for the recycling of waste PV modules per unit area. The release of such policies will bring a positive effect on investment in PV module recycling.

5.2.2 Proposed standard strategies for National Standardization Administration:

① Set higher standards for processing techniques and the core parameters involved

Although the most recent standard related to PV module recycling specify the requirements to be met by different processing technologies and set standards for the purity and recycling efficiency of various materials, there is still room for improvement in these standards. Taking the purity of the material as an example, the recovery purity requirement for silver and copper is 80% (National Standard Full Text Disclosure System, 2021), which is not high under the current level of technology. Raising these standards also raises the threshold for recycling to a certain extent, and is expected to remove some small workshops with low technical maturity from the market.

② Develop standard to determine whether PV modules are wasted

As analyzed in Chapter 4, there are currently two national standards for PV module recycling but do not deal with determining whether PV modules are discarded. This standard is critical in the PV recycling industry. On the one hand, it creates a clear dividing line between the concepts of module recycling and module repairing. On the other hand, at present, many PV modules are not completely scrapped, and the owner of the module has insufficient basis for judging whether to scrap. This gives small workshops the opportunity to profit by reselling PV modules that are not completely scrapped to Africa, the Middle East and other places for profit (NetEase, 2023a). Once the National Standardization Administration sets the standard to determine whether the modules are obsolete, the living space of these small workshops will be squeezed. In this way, market order can be maintained. According to the practitioner’s point of view, an important criterion for judging whether a PV module is abandoned is the attenuation rate of the module, so the relevant standard can be set at a certain value, such as 30% (Interviewee A). When the PV module is tested and found to have an attenuation rate of more than 30%, it is scrapped.

5.3 Chapter reflection

In this chapter, strategies to enable large-scale diffusion of PV module recycling in China are analyzed. The first part analyzes several niche introduction strategies, mainly from the perspective of the enterprise. The second part analyzes the strategies that can be adopted from the perspective of policy makers and standard setters. The combination of these two components can reduce the barriers that arise from partly complete or incomplete parts of each building block and influencing condition.

It should be noted that for the vast majority of the niche introduction strategies listed in section 5.1, there is no direct evidence that they have been used by enterprises, except for collaboration niche strategies. It is a common form of cooperation for enterprises to conduct research projects with scientific research institutions and universities. However, the information that can be found is relatively limited, only Yingli Group, Changzhou Ruisai Environmental Protection and some other PV module recycling companies and their partners can be found. It is also unknown whether this niche strategy is used by a wide range of other PV module recyclers. Other niche strategies in section 5.1 are more likely to be recommendations for relevant enterprises. Considering the limited information collection sources for the study case, the actual effects of these niche strategies need to be further verified. In addition, as mentioned earlier, policy makers and standard setters play a very key role in China's PV recycling industry. The lack of market management policies and standards to judge whether the modules are scrapped has seriously hindered the large-scale proliferation of PV module recycling. Therefore, section 5.2 provides strategies that can be adopted from the perspective of policy makers and standard setters.

6. Conclusion and discussion

This chapter aims to give the conclusion of the research. At the same time, the limitations in the research process and the further research direction are discussed. The chapter is structured as follows: First, sub-section 6.1.1 answers six sub-questions, and on this basis, sub-section 6.1.2 answers the main research question. Sub-sections 6.2.1 and 6.2.2 then reflect on the research done and discuss the limitations of the research. Sub-section 6.2.3 discusses the practical implications of this thesis and gives the measures that can be taken by different actors. Sub-section 6.2.4 illustrates the scientific implication of this thesis. Finally, further research directions are explored in sub-section 6.2.5.

6.1 Conclusion

6.1.1 Answers to sub-questions

1: Which waste silicon PV module recycling technologies have the development prospect in China?

The purpose of this research sub-question is to clarify and understand what existing recycling technologies for used PV modules include and how to classify them through desk research and literature review. Through preliminary screening, several typical component recovery technologies are obtained, which lays a foundation for the subsequent technical evaluation. Usually, waste PV modules need to be pre-treated, that is, manually or mechanically remove junction boxes, cables, etc. Processing the rest involves module recycling technologies. This part of the recycling technology includes three categories: downcycling, cycling and upcycling. Downcycling and cycling are not within the scope of this thesis since they cannot ensure the quality of recovery. For upcycling, two steps are required: the first step is the delamination of components, and the second step is the recovery of silicon and valuable metals. After screening, three typical recovery technologies were selected in the first step: thermal delamination, mechanical delamination and chemical delamination, and their corresponding treatments were two-stage pyrolysis, high-voltage pulse and addition of organic reagents. Similarly, for the recovery of valuable metals in the second step, three typical recovery technologies were selected: hydrometallurgy, electrochemical assisted leaching, and wire explosion. As for all the above-mentioned technologies and processing methods, they have either been put into practical use by enterprises or have been verified as feasible in laboratories, so they have typical characteristics and development potential in China. Overall, after the selection of three typical processing technologies in each step of the waste PV module recycling, this sub-problem is solved, and it also provides objects for subsequent evaluation.

2. How to develop a set of criteria for assessing their strengths and weaknesses?

The purpose of this sub-question is to build an evaluation system to evaluate the typical waste PV module recycling technologies selected in sub-question 1. In this evaluation system, a number of criteria were developed. These standards, on the one hand, cover the characteristics of module recycling technologies as fully as possible from multiple perspectives. On the other hand, they should facilitate intuitive and effective comparison of the performance of different technologies. For different PV module recycling technologies, its economy and technical effectiveness are the two most easy to think of evaluation criteria. At the same time, considering that in the use of some technologies (such as hydrometallurgy), will produce harmful pollutants to the environment, so the environmental protection of the technology is also a standard that needs to be evaluated. In addition, given that these module recycling technologies need to be developed on a large scale in China in the future, their suitability is also very important. Finally, other social factors should also be looked at as a criterion. It mainly includes the acceptance of the technology by the public and the current practical use of the technology. The above five criteria form the answer to this sub-question, they are: (1) Economy. (2) Environmental protection. (3) Technical effectiveness. (4) Applicability. (5) Other social factors. The pros and cons of different module recycling technologies can be measured against them.

3. How well do these technologies perform against this set of criteria, and which one is best?

The purpose of this sub-question is to put the selected typical waste PV module recycling technologies into the established evaluation system for evaluation, so as to obtain the performance of each technology. On this basis, the best performing technology is obtained, which is the most suitable PV module recycling technology for China's future large-scale development.

To answer this sub-question, a desk research and literature review were conducted, and a combination of quantitative and qualitative methods were used in the evaluation process. In order to quantify the performance of each technology and facilitate the grading, the different proportions of the five criteria in the evaluation system in the final grade were given. This division of proportion took into account the importance of each criterion. Applicability and technical effectiveness are the most important, each accounting for 25% of the total score. Second is the criterion of economy, accounting for 20% of the total score. Environmental friendliness of technology and other social factors were the least important compared to other criteria, each accounting for 15% of the total score. At the same time, the performance of each technology under each criterion is reflected by the five scales of 'the best', 'better than average', 'average', 'worse than average' and 'the worst', which represent a progressively decreasing score from 5 points to 1 point. It should be noted that for the different steps of PV module recycling, the technologies involved are evaluated separately. That is, the evaluation of the three recovery technologies in the module delamination step and the three recovery technologies in the valuable metal recovery step are carried out separately and without interference. The final evaluation results are as follows: for the three recovery methods in the first step: thermal delamination, mechanical delamination, and chemical delamination, the final scores are 3.05, 3.65, and 3.45, respectively. For the three recovery technologies in the second step: wet metallurgy, electrochemical assisted leaching and wire explosion, their final scores were 3.35, 3.2 and 2.85, respectively. It is clear that mechanical delamination and hydrometallurgy are the best performing recovery treatment technologies in the first and second steps of PV module upcycling, respectively. This sub-question is thus answered.

4. How well is the Technological Innovation System for waste crystalline silicon PV module recycling technology developed in China?

The purpose of this sub-question is to explore, from an enterprise perspective, which actors and factors are needed to diffuse specific module recycling technologies at scale, using the technological innovation system framework. It should be noted that the initial research object of this sub-question is the module recycling technology that has the best evaluation performance in sub-question 3. However, through the desk research, it is found that due to the diversity of module recycling technologies, there are many enterprises engaged in relevant technology research in China, and they have adopted different kinds of recycling technologies, mainly in the two categories of physical and chemical methods. The best performing combinations of recycling technologies identified in sub-question 3 are only two of the broad range of technologies. This leads to a problem: if the thesis sticks to the best-performing recycling technologies as research objects, it can be difficult to find and gather information about businesses that are using them through desk research alone. If the relevant personnel of the enterprise are interviewed, it is also relatively difficult. On the one hand, they may be reluctant to disclose too much information because of the secrecy of the technology. On the other hand, collecting information from only one or a few companies will make the research content too thin. To sum up, the scope of the research is expanded, no longer limited to a specific module recycling technology, but to look at the entire PV module recycling industry in China. All companies engaged in PV module recycling in China were analyzed to explore from their point of view how to scale up the technology being developed and used.

In order to answer this sub-question, it is needed to analyze the basic situation of the seven building blocks in the TIS framework adopted in this thesis. The information for judging these blocks as complete, partially complete, or incomplete comes mainly from desk researches. After analysis, it is found that except for the incomplete building block of product price, the other six blocks are partially complete. In China's PV module recycling market, only individual companies have the ability to provide target customers with products that ensure quality and performance. There is no convincing evidence that all companies in the industry have this capability. Therefore, the building block of ‘product performance and quality’ is partially complete; For leading PV enterprises, the price of the module recycling products they provide is not yet known, but for high-tech enterprises specializing in PV recycling, the high cost is incompatible with the large-scale diffusion of the product, so the building block of ‘product price’ is incomplete; At present, only a small number of PV module recycling enterprises have the capacity of batch recycling, but the scale of processing still has a large room for improvement, so the building block of the ‘production system’ is partially complete; The building block of ‘complementary products and services’ is partially complete. On the one hand, it is not difficult to regularly test the PV modules that are being used (Interviewee A). And large PV manufacturers can provide maintenance and repair services for the modules. But on the other hand, the treatment of pollutants in the recovery process need further research; The network of participants in the supply chain is emerging, but it is not yet possible to find specific information about some of them (mainly recycling equipment suppliers and chemical reagent suppliers), which makes it impossible to analyze whether there is collaboration among the different actors, so the building block of ‘network formation and coordination’ is partially complete; Although leading PV companies and companies specializing in PV recycling have clear target customers (Interviewee A), customer segmentation is not yet completed. They have a long way to go in determining which companies they can work with in the future that have a demand for recycled materials. Therefore, the building block of ‘customer’ is partially complete; For PV module recycling, the Chinese government has issued a number of policies and standards. However, there are still large policy and standard gaps to be filled, which mainly focus on subsidy policies, policies to regulate the market, and criteria to judge the abandonment of PV modules (Interviewee A). Therefore, the building block of ‘innovation-specific institutions' is partially complete.

The fourth sub-question is answered by filling the information and judging the status of each building block in TIS framework. It can be seen that there is no building block in a complete state, which fully shows that China's PV module recycling industry is still in its infancy, facing many barriers in achieving large-scale diffusion, and different types of actors need to develop and implement strategies to overcome these barriers.

5. What is influencing the current development of the Technological Innovation System for waste crystalline silicon PV module recycling technology in China?

This sub-question aims to explore the conditions that affect the TIS building blocks. These influencing conditions explain the problems in the formation of TIS building blocks, and thus point to the reasons that hinder the large-scale diffusion of PV module recycling in China (Ortt, 2022). There are a total of seven influencing conditions, six of which, except for accidents and events, affect at least one building block (shown in Figure 9). The influencing condition of 'knowledge and awareness of technology' affects three building blocks, resulting from the lack of knowledge of PV module recyclers in ensuring the quality of recycling, scaling up recycling and dealing with the pollutants generated by recycling; The influencing condition of 'knowledge and awareness of application and market' also affects three building blocks. On the one hand, module recycling companies lack a full understanding of the market structure, resulting in product prices that are incompatible with large-scale diffusion. On the other hand, some target customers (enterprises with demand for recycled materials) have insufficient understanding of the product, and some participants in the supply chain (recycling equipment suppliers and chemical reagent suppliers) have insufficient understanding of the recycling process, which also leads to the partial completeness of building blocks; The influencing condition of 'natural, human and financial resources' is partially complete. The lack of adequate financial resources has led to PV module recycling companies being unable to upgrade technology to ensure product performance and scale recycling. Thus, this influencing condition explains the partial completeness of the two building blocks: product performance and quality, and production system; The influencing condition of 'competition' is incompatible with large-scale diffusion. The chaotic market order and unfair competition environment lead to too high product prices (NetEase, 2023a), and make PV module recycling enterprises do not have enough power to ensure product performance and quality; The influencing condition of 'macro-economic and strategic aspects' has an impact on policy and standard setting. Due to the repeated impact of COVID-19, China's economic development situation in 2022 is not optimistic, resulting in the government placing the policy center on economic recovery, without making clear policy provisions for the recycling of PV modules; The influencing condition of ‘socio-cultural aspects’ is not compatible with large-scale diffusion. This is mainly because the small workshops that enter the module recycling market have a mercenary mentality, disrupting fair competition and leading to excessively high product prices (NetEase, 2023a). On the other hand, the conservative mentality of some module recycling companies has delayed them from taking the step of testing large-scale recycling processing (NetEase, 2023a), which has also led to the partial completeness of the building block of production system. It should be noted that the above answers are largely derived from desk research, with part of the analysis based on interview with the practitioner. It can be found from the answer that there are many barriers that hinder the large-scale diffusion of PV module recycling in China, and corresponding effective strategies need to be introduced to eliminate them one by one.

6. What strategies could be adopted to enable large scale diffusion of waste silicon PV module recycling technologies in China?

The purpose of this research sub-question is to explore the strategies that need to be introduced for the large-scale diffusion of waste PV module recycling in China, including their respective types, introduction times and scale. To answer this question, a combination of literature review and desk research was used. First, from the perspective of enterprises, they can adopt six niche introduction strategies, including demo, experiment and develop niche strategy, subsidized niche strategy, educate niche strategy, collaboration niche strategy, geographic niche strategy and top niche strategy. These niche strategies hold the promise of removing or mitigating barriers to large-scale diffusion. However, as mentioned earlier, the above strategies are from the perspective of the enterprise, and they have no influence on policy or standards. The lack of some key policies and standards has seriously hindered the large-scale diffusion of PV module recycling in China. Therefore, the strategies that policy makers and standard setters can adopt are suggested respectively. For their part, policymakers can set policies to regulate markets and stimulate investment; For standard setters, they can develop criteria for determining whether PV modules are discarded (Interviewee A) and increase the minimum requirements for relevant parameters in the PV module recycling process.

6.1.2 Answer to the main research question

How can Chinese PV module recycling companies scale up a new recycling technology?

Based on the answers to the six sub-questions, the main research question is answered as follows: First of all, there are many types of PV module recycling technologies, and their respective advantages and disadvantages are also different. Most of them have not been validated for scale recycling in China, so the gap between them is not that significant. Nevertheless, the evaluation of the technology in this thesis is based on a number of factors, especially the analysis of its suitability for use in China. In this way, the technology that performs best in the evaluation becomes more convincing that it is more suitable for large-scale diffusion in China. As the evaluation results show, the use of mechanical module delamination and the use of hydrometallurgical technology for the recovery of valuable metals is a combination of technologies suitable for the scale development of PV module recycling enterprises in China.

Secondly, if PV module recycling is to develop on a large scale in China, it requires the efforts of multiple actors, listed as follows:

1. For PV module recycling companies, the measures that need to be taken can be divided into three aspects. First, continuous research and development of PV module recycling technologies are needed to ensure the quality of recycling services provided by enterprises by improving core parameters such as material recovery and purity. At the same time, it is necessary to speed up the research on batch recycling technology and improve the capacity of enterprises to dispose of waste PV modules. In addition, regarding the treatment of pollutants in the recycling process, enterprises also need to invest money and time in the development of relevant technologies. Regarding the promotion and research and development of technology, PV module recycling enterprises can strengthen cooperation with scientific research institutions and universities, and make full use of these partners to provide experimental sites and technical support. Second, PV module recycling companies need to identify their target customers, especially those who have a demand for the valuable materials obtained from recycling. This can be achieved by introducing demo, experiment and develop niche strategy and top niche strategy. Third, module recycling companies need to identify the participants in the supply chain, especially the suppliers of recycling equipment and chemical reagents. When the scale of module recycling is scaled up, enterprises will be more closely associated with these suppliers. Clarifying the information of these suppliers and strengthening cooperation will help the formation and coordination of the network.

2. For policymakers and standard-setters, there are important policy and standard gaps that need to be filled. For policy makers (the National Energy Administration and the Ministry of Industry and Information Technology and some other departments), it is

necessary to formulate subsidy policies on PV module recycling, and could also give module recycling enterprises a part of the relevant technology research and development subsidies. Faced with the current chaotic module recycling market, it is necessary for government departments to formulate policies to regulate the market in order to maintain market order and fair competition. In addition, policy makers also need to consider introducing incentives to encourage investment in the PV module recycling industry. Second, for the standard-setters (the National Standardization Administration), it is important to develop standards to judge whether PV modules are abandoned. With such standards, companies and owners of centralized PV plants can determine whether modules need to be recycled. On the other hand, there is a need to further improve the standards regarding the core parameters of the recycling process, especially the recovery rate and material purity. In this way, the living space of small workshops is squeezed, which brings a good competitive environment for formal PV module recycling enterprises.

It should be pointed out that the large-scale diffusion of waste PV module recycling in China requires the joint efforts of multiple actors. Although the analytical framework used in this thesis is based on an enterprise perspective, considering that the PV module recycling industry in China is still in its infancy, policy and standard intervention by the government and standard-setters are essential, and the combination of the two constitutes the answer to the main research question.

6.2 Discussion

6.2.1 Reflections

This thesis aims to explore how to make the recycling of waste PV modules spread on a large scale in China from the perspective of enterprises. The research is mainly divided into two parts: First, different types of PV module recycling technologies are evaluated, and the best performing recycling technologies are obtained. This part answers the first three research sub-questions. The second part applies the TIS framework to the PV module recycling industry in China. By analyzing the status of building blocks and influencing conditions, the barriers to large-scale diffusion are identified and corresponding strategies are specified. This part answers the last three research sub-questions.

Reviewing the first part, it can be found that the evaluation performance of different technologies is effectively quantified by dividing the proportion of each standard in the total score, and using the relative scale to measure the performance of various technologies under different standards and giving corresponding scores, which makes the comparison between technologies easier to achieve. It should be pointed out that the construction of technical evaluation system is subjective. This is mainly reflected in determining the proportion of the five standards in the total score, and formulating the corresponding score for each scale. In fact, it seems hard to be absolutely objective. Due to the large number of criteria, their importance is also different. Simply dividing their share of the overall score equally fails to highlight the difference in importance. In this thesis, the author believes that applicability and technical effectiveness are the key to the large-scale diffusion of PV module recycling technologies in China, so these two standards account for the largest proportion. Considering that environmental protection has not been the focus of too many companies, and the public does not know much about module recycling, there is little difference between various technologies when it comes to acceptance, so environmental protection and other social factors account for the lowest proportion of the overall score. In addition, the matching of the scores represented by the five scales used in the evaluation from 5 to 1 is in a sense an effort to ensure objectivity. It is also important to note that although the actual use of module recycling technology is mentioned in the criterion of other social factors, it is still not absolutely objective. This is because it is not possible to know exactly what technologies are used by PV module recycling companies based on desk research and literature review. In particular, it is difficult to get specific information about the technologies being used by small module recycling businesses. Also, the vast majority of large recycling companies either generally advertise that their recycling methods are based on physical or chemical principles, or do not disclose technical details at all. However, the basic principles, operation steps and other information of the evaluated technologies can be fully grasped through literature review. In this case, the difficulty in obtaining information about recycling technologies from the enterprise is not fully matched with the adequate information access of the technology itself, resulting in a limitation in the relevant assessment, which will be discussed later in the limitation.

Attention is then turned to the second part of the thesis. The TIS framework fits well with this study. As the core role in the PV module recycling industry, how to act is particularly critical for module recycling companies. The TIS framework does a good job of analyzing the obstacles to the large-scale diffusion of PV module recycling from the perspective of enterprises, and on this basis, developing solutions. As far as the analytical framework itself is concerned, it covers a number of core elements related to the development of innovative technologies: producers of the production system, participants in the supply chain, target customers, etc. At the same time, factors such as policy and competition are also included. The combination of these TIS framework components provides a comprehensive perspective for analyzing the current situation of PV module recycling in China. The results of the analysis show that there are four main obstacles to large-scale diffusion: First, the lack of key policies and standards. Second, PV module recycling enterprises do not clear all the target customers. The third is the absence of some actors in the supply chain. Fourth, module recycling technology and related supporting technologies are not mature enough. By analyzing the existing barriers, the corresponding solution strategies are also proposed. However, there are fewer cited sources that can be found through desk research, and they are mainly divided into three categories: first, the official promotional websites of companies engaged in PV module recycling. The second is a number of news sites that report on PV module recycling technology seminars led by social organizations. The third is the views and prospects of the PV module recycling industry published by some journalists after research and interviews. Compared with academic papers, there is a gap in the rigor and persuasiveness of these reference sources. But unfortunately, there are very few academic papers related to the PV module recycling business conducted by Chinese companies. At the same time, there are some difficulties in contacting the enterprises and trying to arrange interviews. Therefore, the lack of information sources and persuasiveness in a certain sense limits the objective evaluation of TIS building blocks and influencing conditions. Once more in-depth communication with more practitioners, perhaps the assessment results will be different. This is also a limitation of the study and will be discussed later.

Throughout the first and second parts of the thesis, the connection between them is not close enough. In fact, after the first part of the technical evaluation was completed, the results of the evaluation were rarely used in the follow-up. This is mainly because when analyzing TIS building blocks and influencing conditions, the input information is based on the actual situation, for example, which recycling technology is being used by different PV module recycling companies. There is no guarantee that the best performing recycling technology evaluated would be used by the enterprise, so it is difficult to make a close connection between the first and second parts of the thesis. At present, the recycling demonstration lines built by China's PV module recycling enterprises are mainly based on physical and chemical methods, which have achieved high recycling efficiency, reaching 99.7% and 92%, respectively. (Science Net, 2022). Combined with the first part of the thesis, the physical method refers to the realization of module delamination by mechanical method, the chemical method is the realization of module delamination by chemical reagents, and the recovery of valuable metals by hydrometallurgy. From the results of the evaluation in part I, the final score of physical delamination (3.65) is higher than that of chemical delamination (3.45), which is consistent with the higher recovery rate achieved using physical methods than chemical methods. In addition, compared to physical delamination, the final score of chemical delamination technology is not much different. On the whole, China's PV module recycling companies do not need to adjust the mainstream recycling technology they use, whether it is physical or chemical method is a good choice.

Another point worth discussing is that, after the analysis of section 4.2.7, it can be found that the policy system for PV module recycling is not complete, mainly reflected in the regulation of the market and the policy to encourage investment is still in a blank state. This is understandable. Generally speaking, when China introduces energy-related policies, it gradually forms a policy system through continuous supplement and improvement, and this process takes some time. At the same time, relevant policies often do not focus on a certain industry or field in the initial stage, for example, when encouraging the exploration of emerging comprehensive utilization of solid waste, the policy not only mentions the promotion of the recycling of waste PV modules, but also involves the recycling of waste wind power blades and the recycling of waste materials from ships (The State Council, 2022a). With the advancement of time, when a certain industry is more and more valued, special policies for it will be implemented, and gradually form a policy system related to the industry. It is foreseeable that due to the urgency of PV module recycling, special policies will soon be introduced to gradually improve the policy system. In China, on the other hand, policy implementation is fast and effective. In particular, the policies implemented by the central authorities will be implemented by all localities in a very short time. Overall, the incomplete policy system for PV module recycling at this stage is not a big problem. In the short term, the policy system will be supplemented, and new policies can be implemented quickly.

6.2.2 Limitations

After the above reflection on the thesis, several limitations related to the research are listed as follows:

① The number of PV module recycling technologies evaluated is relatively limited. This is reflected in the different technologies involved in the recycling step of module delamination. As described in Chapter 3, three processing technologies: thermal delamination, mechanical delamination and chemical delamination, can be used to separate the layers of a PV module. However, each technology can be implemented by different processing methods. Taking thermal delamination as an example, two-stage pyrolysis, burning and radio-frequency heating are all different processing methods to achieve delamination (Wang, 2022). In this thesis, only one of the most representative of them was selected for analysis. On the other hand, most of the evaluated technologies are still in the experimental stage, and the information about their technical principles and processing steps is mainly obtained from scientific research papers. It is not yet possible to prove that the evaluated technologies are necessarily capable of being put into actual production. From this point of view, it seems that not enough attention has been paid to the practical application of module recycling technologies when evaluating them.

② There is a certain subjectivity in the evaluation of different technologies. This is reflected in two aspects: First, there is subjectivity in determining the proportion of different criteria in the total score. This is because there is no strict answer to which is the most or least important for each criterion. Therefore, the weight of the different criteria mentioned above in the overall score may be unreasonable due to the limitation of the author. Secondly, for the evaluation results of different technologies under each criterion, five scales are given in the study. These assessments, for example, that hydrometallurgical technology is better than average in terms of applicability, are subject to strong subjective judgment. In addition to the quantitative method used in the evaluation of economy and technical effectiveness, qualitative analysis was used to evaluate the performance of technologies under other criteria, and more subjective evaluation may also bring irrationality.

③ In the analysis of building blocks and influencing conditions, the input data is limited. As mentioned earlier, the reference sources are basically from the official websites and news reports of module recycling companies, which are insufficient in quantity and persuasion, resulting in a relative lack of analysis depth. At the same time, when analyzing stakeholder map, the information of some actors cannot be found, so they can only be regarded as not existing. This may result in discrepancies with the actual situation. Taking suppliers of recycling equipment and chemical reagents as an example, although the vast majority of module recycling companies do not scale recycling, there is no guarantee that all companies do not have contact with these suppliers. Due to the limited access to relevant information, it can only be summarized as not yet existing.

④ The study was not successful in contacting multiple interviewees to obtain more accurate information on the PV module recycling industry. Invitations to conduct interviews were extended to a number of actors throughout the cycle of the study. These actors include different categories, including: PV module manufacturers, enterprises focused on waste treatment and resource reuse, enterprises focused on PV module recycling, third-party testing agencies, social organizations and scientific research institutions. Unfortunately, only one third-party company (Interviewee A) specializing in the inspection of PV modules and PV systems responded to the email and participated in the interview. Although the interview provided a lot of valuable information, the third-party inspection company is not the core actor (PV module recycling companies), and it do not have a deep enough understanding of the current status of elements such as module recycling technologies, business models, and target customers (Interviewee A). Overall, the problem of insufficient interviews is both a limitation and a regret.

⑤ Following the steps in the use of the TIS framework, after the niche strategies are developed, the final step is to regularly monitor the status of the TIS building blocks and influencing conditions to determine if the strategy needs to be adjusted or a new strategy needs to be developed (Ortt, 2022). This step was not reflected in the thesis. Considering that the PV module recycling industry in China is still in its infancy, repeated testing of the status of building blocks and influencing conditions is of little significance in the short term. This work therefore lends itself to further research, which is discussed in section 6.5.

6.2.3 Practical implication

This study has two practical implications. First, the evaluation of various typical PV module recycling technologies shows their advantages and disadvantages in various aspects. This allows research institutions and universities to improve on the weak side of a technology. For example, the use of reagents for chemical delamination is not environmentally friendly. Relevant research units can set the future direction of improvement to the treatment of pollutants in the recovery process. In addition, the evaluation results of various technologies have also given PV module recycling enterprises some inspiration. The technologies with the highest scores have a lot of potential and can be taken into account if they are not already being used.

Second, the results of the study provide recommendations for action by multiple actors in the PV module recycling industry:

① For PV module recycling companies, continuing to improve the core parameters of recycling technologies (such as recovery rates) is one aspect. At the same time, how to expand the scale of recycling and deal with the pollutants generated by recycling is also an urgent problem to be solved. These technological improvements can be achieved through project cooperation with research institutions and universities, as well as joint research and development with suppliers of recycling equipment and chemical reagents. Another significant barrier is that some of the current target customers for PV module recycling businesses are unclear. This is reflected in the fact that for the valuable materials recovered, it is not clear what companies are in demand for this, and what specific requirements they have for the purity and quantity of materials. Therefore, identifying target customers, mastering their needs, and taking this as the research and development goal to improve the recovery rate and purity of materials is another aspect worthy of attention.

② Filling the gaps in policies and standards is a very important step for government departments and National Standardization Administration. The current chaotic PV module recycling market needs policies to regulate; The problems of high recovery costs and insufficient investment and research and development motivation of module recycling enterprises also require government to formulate subsidy and incentive policies. It is also an important task for the National Standardization Administration to determine the criteria for judging whether PV modules are abandoned as soon as possible.

③ Scientific research institutions and universities can carry out in-depth cooperation with module recycling enterprises, make full use of experimental sites, and test potential recycling technologies and their supporting services. On the other hand, they can regularly lead academic exchange activities in the form of seminars, so that enterprises can more accurately grasp the trend of technology improvement and industry development.

④ Suppliers of recycling equipment and chemical reagents can strengthen ties with module recycling companies, strengthen network collaboration by learning the principles of recycling technologies and mastering the entire recycling process, and jointly contribute to the improvement of technologies. In addition, companies in need of recycled valuable materials can participate in seminars, information sessions and other activities to learn more about the products offered by module recycling companies and decide whether to cooperate with them in the future.

6.2.4 Scientific implication

The scientific implication of this thesis can be divided into three aspects. First, the thesis sets different criteria for the comprehensive evaluation of a variety of PV module recycling technologies. These criteria cover as many factors as possible, such as the cost of using the technology, the effect of using the technology, the degree of application, whether it is environmentally friendly, and whether it can be recognized by the public. Compared with some existing literature comparing different PV module recycling technologies, the evaluation criteria of this thesis are more extensive and comprehensive, especially in the two criteria of environmental protection and applicability, which are often ignored by most studies. Therefore, the analysis results fill the academic gap in this aspect. The results obtained, although subjective, can also show the priority of some technologies when there is a large score difference between them.

Second, as mentioned in section 2.2, much of the literature that uses the TIS framework to analyze an innovative technology focuses on its basic situation during a past period of development, but at this stage the technology is already mature. However, this thesis is different in case analysis. China's PV module recycling industry is in the early stage of development, and many PV module recycling technologies are not yet mature, and how the industry and technology will develop in the future is unknown. Therefore, the object of analysis using the TIS framework is no longer the situation of a technology that has been developed over a period of time, but a new innovative technology that has just undergone short-term development and the future is unknown. This enriches the use of TIS framework to some extent.

Thirdly, this thesis analyzes in detail the current situation of China's PV module recycling industry, the recycling technologies used by various enterprises, and the barriers that need to be broken through to enable related technologies to enter the stage of large-scale diffusion. As mentioned in section 2.2, there is not enough literature to analyze the PV recycling industry in China, what barriers need to be broken through for further development of the industry, who are the actors in the industry and what actions they need to take. These academic gaps are supplemented in this thesis.

6.2.5 Further research

Based on the limitations of the research and the thinking on the development direction of

China's PV module recycling industry, further research is listed as follows:

① For the module delamination of the first step of recovery, layering methods that are not evaluated in the thesis can be evaluated according to a similar evaluation process. This mainly refers to burning and radio-frequency heating in thermal delamination, hot knife, laser irradiation and milling in mechanical delamination and the addition of inorganic reagents in chemical delamination. Through such an evaluation, the integrity of the study will be supplemented.

② Try to contact the interviewees in more ways. The PV module testing company that has been contacted may be a breakthrough. After understanding that the company is closely connected with many companies engaged in module recycling (Interviewee A), it may be possible for the company to act as an intermediary, so that the author can contact with persons in charge of module recycling companies to understand the first-hand information of the industry. Based on the results of more interviews, the TIS building blocks and influencing conditions will be evaluated again to determine their status.

The number of interviews is maintained at around ten, and more importantly, they need to involve a sufficient number of industry actors, including large PV module manufacturers in China, enterprises engaged in recycling and resource reuse, enterprises that have a need for the use of recycled materials, high-tech enterprises specializing in PV module recycling, scientific research institutions and government departments. The information provided by different interviewees can complement each other. Interviews with large PV module manufacturers in China are expected to provide an overview of the volume of used PV modules, especially in northwest China, and the size and number of centralized PV plants that need to be recycled. In addition, details of the recycling technologies used by these leading Chinese PV companies are also available; Interviews with high-tech companies specializing in PV module recycling are expected to obtain details of the advanced recycling technologies they use, including the theoretical basis, recycling efficiency, etc. At the same time, the business model of these companies, especially their cooperation with centralized PV plants, can be obtained; Interviews with companies engaged in resource recycling, as well as companies that have a demand for recycled materials, can obtain detailed information about the materials they recycle, as well as their trading methods and subsequent uses. Interviews with scientific research institutions are expected to gain information on the most advanced PV module recycling technologies and their development prospects; Interviews with the government are expected to predict the types of policies to be introduced in the future, as well as specific methods to maintain market order and fair competition. With the above information obtained in interviews, it will be very helpful to re-evaluate the building blocks and influencing conditions, and they are absolutely based on the actual situation of the industry, which can make the future research of the thesis more rigorous and convincing.

③ The transportation of PV modules and recycling equipment is critical if module recycling is to large-scale diffuse in the future. Further research can take it as a direction. Interviewing module recyclers and transport companies about their current collaborations and thinking about ways to collaborate in the future is one envisaged research approach.

④ For a period of time after the Chinese government and the Standardization Administration fill the policy and standards gaps, the status of the TIS building blocks will be regularly monitored to assess whether adjustments or new strategies are needed. This step is also the last step in the actual use of the TIS framework, ensuring the integrity of the use of the framework.

⑤ Countries other than China can be used as research targets to gain an in-depth understanding of their domestic PV module recycling. Considering that the currently available reference sources on the recycling of PV modules in China are few and not persuasive, it will be of great reference significance to know the development of the recycling industry in other countries. Taking the European Union as an example, on the one hand, its work on PV module recycling was carried out earlier, and relevant policies, standards, business models, recycling technologies, etc., can be learned and used for reference by China. At the same time, the information that cannot be collected or the missing actors in China's PV module recycling network can perhaps be found in the examples of other countries. This can also provide reference for domestic practitioners. On the other hand, reference sources related to PV module recycling in other countries in the world will be more and more convincing. Therefore, using the steps in the second part of the thesis to analyze other countries is an important part of further research.

⑥ Strengthening the connection between the first part and the second part of the thesis is also one of the directions for further research. The initial research idea is to analyze the TIS framework for the combination of technologies that perform best in the evaluation (i.e., module delamination using mechanical methods and recovery of valuable metals using hydrometallurgy), with a full understanding of which companies are developing or using them. In contrast to this study, the object of study changed to these specific companies, and the core products became these best-performing technology combinations. To assess the status of the building blocks and influencing conditions, the input information is primarily derived from interviews with enterprises that use these technologies. This part of the work needs to be combined with the above-mentioned scheduling more interviews. In addition, it may be effective to immerse the author in the company, attend internal meetings and events, etc., to learn more information, although it seems difficult.

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Appendix

1. Interview with practitioner of PV module inspection

The interviewee is from a state-owned enterprise in China, which mainly supervises, tests and certifies the quality of PV products, and is a professional and authoritative third-party testing institution. The interviewee himself has more than ten years of working experience in the field of PV product testing.

Before the interview, the interviewee stressed that the name of his company and his personal name should not be disclosed in the thesis. Therefore, in this interview transcript, the practitioner is referred to as the interviewee A.

-What specific PV related inspection does the company do?

There are three types of testing for PV modules: 1. The company conducts basic certification of the new PV modules according to the international general testing standards. The testing items involved here include: electrical testing, anti-aging testing, mechanical testing and safety testing. 2. Test the performance of PV modules in special application environments. These special environments are usually built in the laboratory, including high temperature and humidity, sand and dust environments. 3. Take the PV modules to the actual PV power station for operation testing. These PV power stations are usually under special circumstances. For example, there are test stations in Mohe, the northernmost and coldest city in China, and in the hot and dry region of Turpan in Xinjiang.

As a testing agency, we also test PV power stations, which are mainly divided into four situations: 1. The owner of the PV power station entrusted us as the supervisor to move in the PV power station. The main work is to sample all newly installed PV modules. 2. Installation test. New PV modules are sampled when they arrive at the PV power station but have not yet been formally installed. 3. Before the PV power station is officially put into operation, the entire power station is tested. At this time, it is not only the quality inspection of the modules, but the inspection of the entire station, so there are many more inspection items, including the testing of shading loss, series and parallel loss and insulation performance, etc. 4. After the PV power station has been used for a period of time, the company is commissioned to test it. This is often the case when the owner of PV power plant feels that the module performance is not up to standard and commissions us to inspect it.

- Have any major PV manufacturers commissioned you to test and certify their new produced PV modules?

This is inevitable. As I mentioned in the previous question, the first item in PV module inspection, basic certification, is related to it. When a batch of new PV modules leave the factory, the PV module manufacturers need to deliver them to us for testing, and after obtaining basic certification, they can be promoted by their company's sales staff.

- Is the company doing or planning business related to PV module recycling?
- In my thinking, when a PV module is scrapped, a third party needs to make a judgment on it, otherwise it may still be within the scope of being repaired. What do you think about that?

My understanding is that when judging whether a module can still work, there are no more than three cases, the first is that the PV module is working properly, and the second is that the module is not usable. The third is that its use effect is not good. And this is basically a subjective judgment. For example, when the power attenuation of a PV module is more than 20%, then I think it is no longer useful. At this time, a third-party agency is commissioned to detect, and if the attenuation rate is truly more than 20%, then replace the module. But that number is ultimately subjective. If it can be seen from the appearance that the module has been scrapped, for example, the solar cell is broken, there is no need for third-party detection, because it has lost its basic function.

- In addition to the attenuation rate that you mentioned earlier, do you think there are other important parameters related to PV module obsolescence?

From what I’ve heard, people in the industry are basically thinking about this from a module performance perspective. If you look at it from a security point of view, it's also possible. For example, the back sheet of the PV module is cut open, but it is still running, and if the touch of the staff leads to electric shock in wet weather, it will be a great safety accident. But in general, these criteria or parameters are not clearly defined.

- In view of your years of experience in the industry, in addition to judging the waste of PV modules, what other businesses related to PV module recycling can the testing organization carry out?

The inspection organization usually carries an attribute that it must be a third party. The so-called third party is independent of production and use. The testing agency is only responsible for the authenticity of the data, and does not consider the factors of production and use. Module recycling has become an industry, and there will be specialized supply and demand parties to engage in related business. In my opinion, there are many types of actors in the industry, such as recyclers, power plants, owners, equipment suppliers, etc. As a result, testing agencies, as the only party responsible for the authenticity of the data, can do very little. The only thing that can be done at the moment is for third parties to advise industry actors, based on data, on what kind of PV modules have to be recycled, what modules can be recycled and still be used, and so on. A good example is the attenuation rate mentioned earlier. If the module's attenuation rate exceeds 30%, the third-party organization recommends that the module owner replace it. But I think the owners have a say in whether they decide to recycle or not.

- There are two main forms of trading for PV module recycling: first, module recycling enterprises provide recycling services and collect recycling fees from module owners; The second is that the module owner resells the used modules to the recycling companies. In your opinion, which one will dominate in the future?

I prefer that the owner of the PV module pay the recycling company. It seems to me that this is essentially a delegation that the module owner entrusts the recycling company to process. The second form you mentioned is actually very unreasonable. It is close to reselling used PV power plants to recycling companies, which is not practical. Since module recycling companies do not need to recycle parts of the PV system other than modules, such as inverters. And PV power plants are usually very expensive, I don't think small and medium-sized recycling companies can afford this cost. From another perspective, I think it's a 'who pleads with who' issue, and the core is whether the recycled stuff is good to dispose of. When recycling is well realized and the added value is great, the recycling of such items will be very popular. However, from the current situation, such items as PV modules are very difficult to deal with, usually with environmental pollution. And there is not much recyclable stuff in the modules. Aluminum frame is one of them, but other materials, such as glass, are very cheap to recycle. Therefore, it is the module owners who should 'plead with' the recycling companies to pay them to dispose of the used modules.