

Optimizing the location choice of reverse logistics recycling network for end-of-life photovoltaic modules based on the EPR principle

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ABSTRACT

With the rapid development of the photovoltaic (PV) industry, the collection and recycling of end-of-life PV modules is facing a new challenge. Based on the EPR principle (Extended Producer Responsibility principle), this paper investigates the location choice of reverse logistics recycling network for end-of-life PV modules from the perspective of different stakeholders. In this study, a mixed integer programming (MILP) model is established to optimize the reverse logistics network of end-of-life PV modules with the objective of minimizing the total cost of the reverse logistics network, taking into account a four-tier recycling network system with customers going to the recycling centre, dismantling and processing centre, remanufacturing centre and waste disposal agency, and three recycling solutions are designed according to the EPR principle, and the optimal solution is found with the help of CPLEX software. Optimal solution, so as to determine the siting of facilities in the network and the distribution among each node. We take Zhejiang Province, one of the leading regions in China for promoting distributed PV applications, as the research object, and plan and design the recycling network of end-of-life PV modules in Zhejiang Province, determine the siting of the network as well as the distribution of the traffic to validate the validity of the MILP model, and provide opinions and references for the recycling problem of end-of-life modules in the future.

KEYWORDS

Reverse Logistics; Recycling Networks; End-of-Life PV Modules; EPR Principles; Site Selection Model

1. INTRODUCTION

Since the 20th century, photovoltaic (PV) has seen tremendous increase in both demand and applications worldwide. The total installed PV capacity as of 2019 was 627 GW. The PV power generation market is expected to continue its rapid development in the future, having already established itself as a large-volume market. As a result, questions concerning the long-term availability of essential resources have been highlighted by the growth and development of the new industry of PV module recycling. Amid the global PV overcapacity, China has actively promoted a number of PV-related projects as part of the country's low-carbon transition strategy, boosting the concrete application of PV technology in the country's domestic market. As of 2019, China's cumulative installed capacity of PV power generation reached 204.7 (GW), accounting for 32.6 per cent of the global total, and China is the superpower of PV use in the world and it is making the country a superpower in terms of PV installation and consumption. When the service life of PV power plants reaches 25 or 35 years, the recycling of large quantities of end-of-life PV modules will become a key concern in the future, and therefore the recycling and disposal of end-of-life PV modules is imminent.

In the reverse recycling logistics of the photovoltaic industry, the demand for waste PV modules is greater than the demand for other logistics, and the recycling system is not mature enough due to the lack of relevant policies. Secondly, recycling logistics is one of the primary forms of reverse logistics in the photovoltaic industry. This paper takes the recycling process of photovoltaic as the research object of the reverse logistics of the photovoltaic industry, and the waste photovoltaic modules are recycled and reused in the wave of scrapping of photovoltaic system products that reach the age of the product so that they are recycled and reused. Recycling and reuse of used PV modules to maximize the recycling rate of end-of-life PV modules and to achieve the goal of protecting the environment and promoting the sustainable development of resources. In designing the recycling network for reverse logistics, this paper establishes a recycling network in line with end-of-life PV modules. It optimizes its location selection according to the EPR principle and considers different stakeholders for recycling end-of-life PV modules. The rest of this paper is as follows: Section 2 provides a systematic literature review of the current status of domestic and international research on end-of-life PV modules and research gaps, Section 3 describes the specific recycling process of end-of-life PV modules, as well as data collection and the MILP model, Section 4 describes the study of practical application and data analysis using PV modules in Zhejiang Province as a case study, and Section 5 concludes and discusses the recycling program.

2. LITERATURE REVIEW

In the current rapid development of the PV industry, the end-of-life management of PV modules has become a high-profile issue, and the EPR principle (Extended Producer Responsibility) plays a key role in promoting sustainable life-cycle management. The EPR principle requires producers and manufacturers to participate in the disposal and recycling, which will lead the PV industry to develop in the direction of more sustainable. Against this background, scholars are gradually focusing on achieving a more efficient and sustainable logistics waste management system based on the EPR principle by optimizing the location of the reverse logistics recycling network for end-of-life PV modules. In the past few years, many foreign scholars have focused on the study of end-of-life PV modules, and most of these studies have concentrated on the scale of recycling as well as recycling procedures and recycling networks. Studies on waste generation projections have also shown the need for practical consideration of viable recycling solutions [1]. Several other studies have shown that the economic incentive to recycle most PV modules is unfavorable without additional incentives. Therefore, policies related to producer responsibility should be encouraged to ensure that recycling and recovery programs can be successfully implemented [2].

In the planning of recycling facilities, efficiency in reverse logistics is crucial for the economic viability of PV waste management, which has recently received attention from numerous researchers, with efficiency influencing the cost of recycling in reverse logistics [3]. Wu, J. X. et al. [4] combined recycling cost minimization and carbon emission minimization as two objective functions and established a reverse logistics recycling network system including customer areas, recycling centers, processing centers (including remanufacturing and reuse centers, energy recovery centers) and landfill sites as an integrated system, which achieved the minimization of both economic and environmental objectives. Li, Y. [5] presented a case study on photovoltaic module end-of-life in China, setting multiple objective functions, including module transportation costs, fixed investment costs, and operating costs to minimize expenses and calculating the location of recycling centers when China faces different module end-of-life volumes from 2040-2045. Photovoltaic recycling facilities based on the current PV installations in Germany [6], with the target period set to 5 years and the goal to maximize the number of logistic travel distance and using CPLEX as an optimization solver to find the optimal solution. MILP is a quantitative model applied to supply chain optimization, which uses integer variables to reflect the location of logistics nodes and continuous variables to represent the distance traveled by logistics. Node locations and uses continuous variables to represent supply capacity, processing capacity, and various resource allocations [7], so in the recycling network of PV

reverse logistics, in order to find the optimal siting problem of PV modules, we use the MILP model as the model reference for this study.

In China, relevant departments and governments have not yet introduced policies and legal obligations related to the recycling of end-of-life PV modules. Therefore, the problem of reverse recycling network and optimal siting of end-of-life PV modules in China is still in a research gap, and solving the problem of recycling cost optimisation is a top priority for such programmes. In summary, the literature described above focuses on optimising recycling network models or developing new models from the perspective of traditional end-of-life products, incorporating factors such as minimisation of environmental benefits and maximisation of social benefits, as well as cost or profit objective functions. However, these complex models have not yet been applied to end-of-life management of PV modules. Considering that PV recycling has not been widely implemented in China, this paper focuses on reverse logistics recycling network systems with and without PV manufacturer participation and the cost differences in the PV reverse logistics recycling process. Three recycling scenarios are designed in this study. The difference between the three scenarios lies in the selection of different recycling centre nodes, and the difference lies in the impact of the selection of different recycling centre nodes on the total cost of reverse logistics. For this purpose, the basic MILP model is applied to evaluate the different recycling options comparatively.

3. RESEARCH METHODOLOGY

3.1. Network architecture for recycling of end-of-life PV modules

The European Union (EU) issued the Waste Electrical and Electronic Equipment Regulation (WEEE) in 2002, which is one of the most representative laws and regulations based on the EPR principle. The recycling efficiency of waste electronic and electronic equipment can be promoted under the EPR principle. The Electronic and Waste Equipment Directive 2002/96/EC can be referenced. Several research papers have precisely described the reverse logistics recycling network for various types of waste, such as the reverse recycling network for end-of-life automobiles established, which includes recycling centers, dismantling centers, remanufacturing centers, landfills, etc. The recycling processes for e-waste all contain several of the above logistics nodes. PV waste recycling involves collecting end-of-life modules from end customers, inspecting, dismantling, and distributing them for reuse modules or parts, and properly disposing of other wastes and waste fluids. Therefore, concerning this end-of-life PV waste recycling network, we have established an end-of-life PV module recycling network, including a customer area, recycling center, dismantling center, remanufacturing center, and waste treatment facilities. Figure 1 shows the flowchart of the PV waste module recycling network system.

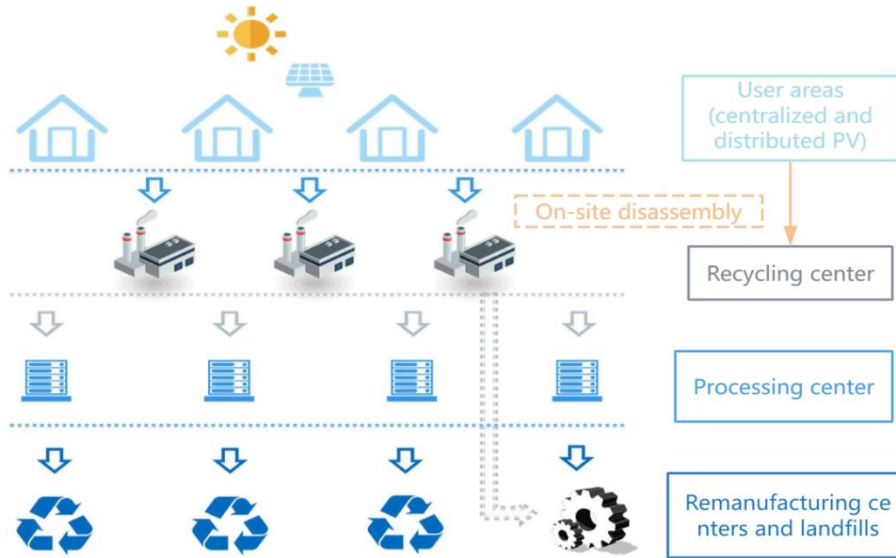


Figure 1. Flow chart of PV waste module recycling network system

3.2. Problem Description

In this paper, we will establish a mixed integer programming (MILP) model with the objective of cost minimization in the end-of-life PV module reverse logistics recycling network system, and considering the EPR principle; we design three recycling center nodes at the end-of-life recycling center, which are government recycling, WEEE recycling factory recycling, and PV manufacturer recycling. The recycling schemes for the three stakeholders are as follows.

3.2.1. Government recycling programme

End-of-life modules at the user end are dismantled on-site by a professional dismantling team dispatched from the government-set recycling center node and collected, inspected, and distributed, and the usable modules are transported to the next level of dismantling and processing center for special dismantling, and then after going through the dismantling and processing center the functional materials are sent to the re-manufacturing center for reuse. The government-set recycling center sends the non-recyclable modules directly to the waste treatment facility for treatment. Non-recyclable components are sent directly to waste disposal agencies by government-set recycling centers.

3.2.2. WEEE recycling plant recovery programme

The end-of-life components of the user end are dismantled on-site and distributed by the dismantling team dispatched from the recycling center node set by the WEEE recycling plant. The other subsequent processes are consistent with the scheme a.

3.2.3. PV Manufacturers Recycling Programme

End-of-life modules at the client end are dismantled on-site by dismantling teams dispatched from the recycling centre node set up by the PV manufacturer. Both usable and unusable modules are transported to the PV manufacturer who inspects, dismantles and reuses functional PV modules, and sends non-recyclable modules to a waste treatment facility for disposal, thus ensuring that the manufacturing company complies with environmental regulations and reduces pollution and impact on the environment. In a reverse logistics recycling system, four types of costs are involved: on-site dismantling costs of end-of-life modules, transport costs, fixed investment costs at each node, and end-of-life module disposal costs at each node. Therefore, this study will develop a mixed integer planning model (MILP model) that minimises the total cost, and the model will be used to find out the optimal transport planning path and the construction location of each node.

3.3. MILP model assumptions

H1: The location of PV equipment users and their end-of-life volume, recycling centers, dismantling and processing centers, remanufacturing centers, and candidate locations for waste treatment facilities can all be known in some way. The selected locations can be known in some way.

H2: The locations of government recycling centres and WEEE recycling centers are known in some way.

H3: The end-of-life PV module recycling network facilities involved in the model have capacity constraints.

H4: Users of PV equipment are divided into two categories: centralized PV and distributed PV.

H5: There are good traffic conditions between the facilities in the recycling network, which will not affect the logistics delivery.

H6: End-of-life PV modules are divided into two categories: crystalline silicon modules and thin film modules, and are recycled and circulated in the recycling network.

H7: The fixed investment cost of similar facility nodes in different locations is the same.

H8: Individual facilities on the same level in the reverse logistics recycling network for end-of-life PV modules are independent of each other and do not circulate.

H9: Only a single type is considered

3.4. Establishment of network planning model

Given that the current domestic recycling of end-of-life PV modules has not yet formed a complete system, the domestic market for end-of-life module recycling and remanufacturing level varies, the level of its revenue can not be accurately described, the recycled end-of-life module remanufacturing or sold into the second-hand market to generate revenue indicators are not applicable to be used as the objective function of the model. Therefore, the reverse recycling network model of end-of-life PV modules established in this study takes the minimization of reverse logistics costs as the objective function, including the fixed investment costs of installing government recycling points, WEEE recycling factories, PV manufacturers' recycling centers, and dismantling and processing centers, the on-site dismantling costs of end-of-life modules, the transportation costs between each node of the reverse logistics, and the processing costs of the products handled by recycling and dismantling and processing centers. The objective function contains Z_1 (fixed investment cost for the construction of recycling facilities in the reverse logistics network for end-of-life PV modules), Z_2 (cost of dispatching personnel from recycling centers for on-site dismantling), Z_3 (logistics and transportation cost between various levels of facilities in the reverse logistics system of end-of-life PV modules), and Z_4 (cost of disposal of end-of-life PV modules at different levels of facilities in the recycling system). The following are the MILP models for the three cases: government, WEEE recycling plant, and PV manufacturing company. The government recycling and WEEE recycling company recycling scenarios are shown in Model 1.

Facility fixed investment costs Z_1 :

$$Z_1 = \sum_{o=1}^O \varpi \cdot W_o + \sum_{t=1}^T \gamma \cdot X_t + \sum_{r=1}^R \rho \cdot Y_r + \sum_{l=1}^L \mu \cdot Z_l \quad (1)$$

Site dismantling cost Z_2 :

$$Z_2 = \sum_{c=1}^c \chi \cdot \delta \quad (2)$$

Total logistics and transport costs Z_3 :

$$Z_3 = \left(\sum_{c=1}^c \sum_{o=1}^o J_{co} \cdot P_{co} \cdot G + \sum_{o=1}^o \sum_{t=1}^T K_{ot} \cdot Q_{ot} \cdot F + \sum_{o=1}^o \sum_{l=1}^L N_{ol} \cdot Vol \cdot I + \sum_{t=1}^T \sum_{r=1}^R A_{tr} \cdot Str \cdot E + \sum_{t=1}^T \sum_{l=1}^L M_{tl} \cdot Util \cdot D \right) \cdot \varepsilon \quad (3)$$

Disposal cost Z_4 :

$$Z_4 = \left(\sum_{o=1}^o \sum_{c=1}^c G \cdot \varphi + \sum_{t=1}^T \sum_{o=1}^o F \cdot Ht + \sum_{r=1}^R \sum_{t=1}^T E \cdot Br + \sum_{l=1}^L \sum_{t=1}^T D \cdot Ql \right) \cdot \varepsilon \quad (4)$$

Therefore the objective function of the construction and operation cost of the reverse logistics recycling network of the model is ;

$$\min Z = Z_1 + Z_2 + Z_3 + Z_4 \quad (5)$$

The constraints of the model:

(a) Capacity constraints of reverse logistics recycling facilities:

$$\theta \cdot Wo \leq \sum_{c=1}^c G \cdot \varepsilon \leq \eta \cdot Wo, \forall o \in O \quad (6)$$

$$\phi \cdot Xt \leq \sum_{o=1}^o F \cdot \varepsilon \leq \kappa \cdot Xt, \forall t \in T \quad (7)$$

$$\sigma \cdot Yr \leq \sum_{t=1}^T E \cdot \varepsilon \leq \lambda \cdot Yr, \forall t \in T \quad (8)$$

$$l \cdot Zl \leq \sum_{t=1}^T D \cdot \varepsilon + \sum_{o=1}^o I \cdot \varepsilon \leq v \cdot Zl, \forall t \in T, \forall o \in O \quad (9)$$

(b) The principle of flow conservation at all levels of facilities in the reverse logistics recycling network:

$$\sum_{o=1}^o G = \tau \cdot \varepsilon, \forall c \in C \quad (10)$$

$$\sum_{c=1}^c G = \sum_{t=1}^T F \cdot \sum_{l=1}^L I, \forall o \in O \quad (11)$$

$$\sum_{o=1}^o F = \sum_{r=1}^R E + \sum_{l=1}^L D, \forall t \in T \quad (12)$$

(c) The proportionality equation between the flow of end-of-life PV modules into the remanufacturing centre and the waste treatment facility:

$$\sum_{l=1}^L F = \alpha \cdot \sum_{c=1}^C G, \forall o \in O \quad (13)$$

$$\sum_{l=1}^L I = (1-\alpha) \cdot \sum_{c=1}^C G, \forall o \in O \quad (14)$$

$$\sum_{r=1}^R E = \beta \cdot \sum_{o=1}^O F, \forall t \in T \quad (15)$$

$$\sum_{l=1}^L D = (1-\beta) \cdot \sum_{o=1}^O F, \forall t \in T \quad (16)$$

(d) Number of facilities constraint limitations:

$$\sum_{o=1}^O W_o \leq \xi \quad (17)$$

$$\sum_{t=1}^T X_t \leq \mathcal{G} \quad (18)$$

$$\sum_{r=1}^R Y_r \leq \psi \quad (19)$$

$$\sum_{l=1}^L Z_l \leq \zeta \quad (20)$$

(e) Other variable constraints:

$$G, F, E, D, I \geq 0, \forall c \in C, \forall o \in O, \forall t \in T, \forall r \in R, \forall l \in L \quad (21)$$

$$W_o, X_t, Y_r, Z_l \in \{0,1\}, \forall o \in O, \forall t \in T, \forall r \in R, \forall l \in L \quad (22)$$

(5) denotes that the total cost of model reverse logistics is minimum; (6)-(9) denote that the four nodes of recycling treatment volume of the recycling centre, dismantling treatment centre, remanufacturing centre and landfill have upper and lower limits, respectively; (10)-(16) denote the end-of-life quantities of components shipped from the customer area to the recycling centre at the level of component recycling rate τ , the end-of-life quantities shipped from the recycling centre to the dismantling treatment centre and the landfill at the level of recycling centre treatment rate α , and the end-of-life quantities shipped from the dismantling treatment centre to the remanufacturing centre and the landfill at the level of dismantling treatment rate β , respectively; (17)-(20) denote that the total quantities of each node established do not exceed the maximum upper limit, and (17)-(20) denote that the total quantities of each node established do not exceed the maximum upper limit. exceeds the maximum upper limit, (21) indicates that the flow rate of each logistics node is non-negative (22) indicates that each node selection variable belongs to 0-1 variable.

3.5. Applied research on recycling network for end-of-life PV modules

As a large PV installation province, Zhejiang Province has supported the utilisation of distributed PV systems since the early 2010s. By the end of 2018, the cumulative installed capacity of distributed PV projects in Zhejiang reached 7.76 GW, ranking first in the country. Therefore, we take Zhejiang Province as the research object and use the above MILP model to plan a regional PV end-of-life module reverse logistics recycling network.

3.5.1. Reverse logistics recycling node distribution

3.5.1.1 User area

In order to simplify the study, this paper divides the PV customer area into a limited number of customer areas, takes each municipal government as the centre of the customer area, and unifies the distributed and centralized PV customer area locations into one location for calculating the PV module end-of-life volume is allocated to each city according to the proportion of population distribution of each city in Zhejiang Province. Table 1 is a table of customer areas in each city of Zhejiang Province.

Table 1. Client areas in Zhejiang Province (per city)

City	Jiaxing	Huzhou	Lishui	Hangzhou	Ningbo
Wenzhou	Shaoxing	Jinhua	Quzhou	Zhoushan	Taizhou

3.5.1.2 Recycling centre

Based on the EPR principle, we consider three stakeholders as nodes of the recycling centre, which are government recycling point, WEEE recycling factory node and PV manufacturer recycling node, and establish three recycling schemes based on the three recycling nodes. Government recycling: there are 11 cities in Zhejiang Province, and it is assumed that there is a government recycling centre in each prefecture-level city. WEEE recycling factory recycling: WEEE recycling factories (i.e., WEEE recycling factories) are mainly engaged in recycling of household electrical and electronic appliances, therefore, WEEE recycling factories are used as the recycling nodes, and the four WEEE recycling factory's are approved by the Ecology Department of Zhejiang Province, two are located in Hangzhou, one is located in Taizhou, and one is located in Quzhou, and these factories are decided by the local government and cover most of the residences in the province. Table 2 is a table of four WEEE recycling companies in Zhejiang Province.

Table 2. Four WEEE recycling companies in Zhejiang Province

City	Company
Hangzhou	Company A
Quzhou	Company B
Hangzhou	Company C
Taizhou	Company D

3.5.1.3 Recycling by PV manufacturers

As there is no domestic policy on direct recycling of PV waste modules by PV manufacturers, we have selected 10 PV manufacturers to directly recycle, treat and reuse PV waste modules in accordance with the Charter of the China Photovoltaic Industry Association, and therefore Scenario 3 will not enter the recycling process below. Table 3 is a list of companies that offer recycling programme for PV manufacturers.

Table 3. Companies with recycling programme for PV manufacturers (per city)

City	Company
Hangzhou	Company E
Taizhou	Company F
Hangzhou	Company G
Shaoxing	Company H
Hangzhou	Company I
Hangzhou	Company J
Huzhou	Company K
Jiaxing	Company L
Jiaxing	Company M
Quzhou	Company N

3.5.1.4 Dismantling and processing centre

It is the most important link in the design of the recycling network for end-of-life PV modules, and is the core of the whole recycling network, and the efficiency of its work directly determines the success or failure of the operation of the whole recycling system. The construction scale of the dismantling and processing centre needs to take into account the processing demand of end-of-life PV modules in the future period, but it also needs to be in line with the reality, and should not be constructed blindly, so as to prevent the waste of resources. There are 11 prefecture-level cities in Zhejiang Province, and in order to be able to cover the whole province, it is set that each city has a dismantling and processing centre.

3.5.1.5 Remanufacturing centre

As of September 2023, the PV membership list was updated in the Constitution of China PV Industry Association, so this paper screens the 763 enterprises of the industry association and selects 51 enterprises related to photovoltaic products in Zhejiang Province, and removes the industry associations and other equipment manufacturing enterprises and material enterprises, etc., and this paper selects and takes out the following 10 photovoltaic enterprises as the candidates of the remanufacturing centre. Table 4 is a table of the ten remanufacturing centres and the cities in which they are located.

Table 4. Ten remanufacturing centres and the cities in which they are located

City	Company
Hangzhou	Company E
Taizhou	Company F
Hangzhou	Company G
Shaoxing	Company H
Hangzhou	Company I
Hangzhou	Company J
Huzhou	Company K
Jiaxing	Company L
Jiaxing	Company M
Quzhou	Company N

3.5.1.5 Waste treatment organizations

After searching the table "Issuance of Hazardous Waste Operation Licence in Zhejiang Province" issued by the Environmental Protection Department of Zhejiang Province and screening the approved

operation mode of the enterprises and their waste treatment categories, the following list of candidate enterprises in Zhejiang Province with operation licence that are in line with the waste treatment organizations of this model is selected and numbered. Table 5 shows the list of candidate companies for waste disposal organizations.

Table 5. List of Candidate Enterprises for Waste Disposal Organizations

City	Company	Annual volume (t)	Number
Hangzhou	Company 1	60000	D1
Hangzhou	Company 2	62500	D2
Hangzhou	Company 3	50000	D3
Hangzhou	Company 4	15000	D4
Ningbo	Company 5	66300	D5
Ningbo	Company 6	4000	D6
Wenzhou	Company 7	11000	D7
Shaoxing	Company 8	18000	D8
Quzhou	Company 9	3000	D9
Jiaxing	Company 10	30000	D10
Huzhou	Company 11	45000	D11
Zhoushan	Company 12	5000	D12
Jinhua	Company 13	30000	D13
Jinhua	Company 14	32000	D14
Taizhou	Company 15	43000	D15
Taizhou	Company 16	50000	D16

3.6. Basic data

3.6.1. Forecast of end-of-life volumes

Over the years, the installed capacity of PV in Zhejiang Province has been ranked among the top in the country, and has shown a continuous growth trend. In the first half of 2023, the installed capacity of PV in Zhejiang Province has reached 28.56 GW. Zhejiang Province is a large province of PV installation and use, so this study takes PV recycling in Zhejiang Province as the object of research. We use the publicly available information from the National Energy Administration and the China Business Industry Research Institute as the research data for this study. The installed capacity of PV in each customer area is distributed to each city in each province in accordance with the population ratio of 11 cities in Zhejiang Province, and according to the BP neural network and market supply A model proposed by Fu, L. Z. [8] study, the end-of-life volume of each customer area in Zhejiang Province in the period of 2025-2035 is predicted, and the end-of-life volume of each customer area in the period of 2035 is used as the statistical data in this study. Table 6 shows the end-use consumption per city in 2035.

Table 6. End-consumption per city in 2035 (MW)

City	Scrap quantity (MW)	City	Scrap quantity (MW)
Hangzhou	2330	Ningbo	1810
Wenzhou	1820	Jiaxing	1040
Huzhou	640	Shaoxing	1000
Jinhua	1340	Quzhou	430
Zhoushan	220	Taizhou	1260
Lishui	470		

3.6.2. Distance between nodes

The distance between the nodes is directly related to the freight costs and is an important parameter in the planning process of the end-of-life parts recycling network. Distance distance is the distance between the nodes of each company (city centre) mentioned above and can be derived from a direct query using Google Maps. We take the example of the user centre to the government recycling node, and other node distances by analogy. Table 7 represents the distance from the customer centre to each government recycling node of the municipality.

Table 7. Distance from the customer centre to the recycling nodes of each city government (km)

Gov User	Jia xing	Hu zhou	Li shui	Hang zhou	Ning bo	Wen zhou	Shao xing	Jin hua	Qu zhou	Zhou shan	Tai zhou
Jia xing	5										
Hu zhou	66	5									
Li shui	266	269	5								
Hang zhou	77	72	199	5							
Ning bo	129	186	226	143	5						
Wen zhou	306	327	93	255	226	5					
Shao xing	80	104	187	42	103	229	5				
Jin hua	214	205	73	141	210	159	140	5			
Qu zhou	269	244	117	193	285	210	205	78	5		
Zhou shan	163	227	279	195	59	266	157	268	344	5	
Tai zhou	240	279	148	212	134	102	174	179	252	166	5

3.6.3. Other data

For the unit transport cost of PV modules, Zhang, Z. B. [9] considered the transport weight, unit price, distance, vehicle type, manpower, loading mode, and the change of the transport market. The transport price of PV modules is affected by the change of transport mode and the factors such as low and high seasons in the transport market and highway tolls, and the results of transport cost are different from the actual results. The result of transport cost is not much different from the actual calculation result, and the data is informative. Therefore, this paper adopts the average data of 0.66 Yuan/t km as the unit transport cost of end-of-life PV modules, and chooses 17.5m semi-trailer model with 36 boxes per car and 26 blocks per box, loading 936 blocks and 17.8t modules in total, i.e., LD=17.8t. At the same time, this paper assumes that the unit transport price will remain unchanged in the coming period and the unit transport price is the same between each node. Table 8 represents the average price per unit of transport between nodes.

Table 8. Average price per unit of transport between nodes

Year	2013	2014	2015	2016	Average
Unit transport price	0.64	0.66	0.70	0.62	0.66

At present, there is no formed recycling network for end-of-life photovoltaic modules in China, but according to the WEEE Directive, end-of-life modules are classified as household electrical appliances for mandatory recycling and treatment, so this paper refers to the relevant fixed investment cost of e-waste, treatment capacity and treatment cost, the investment cost is shown in the table below. Table 9 indicates the fixed investment costs, treatment capacity and treatment costs.

Table 9. Fixed investment costs, treatment capacity and treatment costs

	Fixed investment costs (ten thousand yuan)	Unit processing cost (yuan/t)	Processing capacity (t)
Recycling centre	60	1580	20000
Dismantling and processing centre	216	10530	8000

Photovoltaic modules are composed of backsheets, cells, welding tapes, glass, junction boxes, photovoltaic wires and other photovoltaic components, which are connected in series to obtain high voltage and then in parallel to obtain high current. Since 2000, a number of developed nations have implemented WEEE management. Additionally, numerous mandatory laws and regulations based on the Extended Producer Responsibility (EPR) principle have come into effect, which requires producers to assume responsibility for a product's entire life cycle, particularly collection, dismantling, and recycling at the end of the product's disposal. For instance, the European Union released the Regulation on Waste Electrical and Electronic Equipment (WEEE) in 2002, which is among the most representative laws and regulations based on the EPR principle. Electronic and waste equipment directive 2002/96/EC [10]. According to the WEEE Directive, this paper assumes that all end-of-life PV modules are recycled without loss under the recycling scheme of government recycling and WEEE recycling factories, i.e., $\tau = 100\%$, the ratio of shipment from recycling centres to dismantling centres $\alpha = 85\%$, and the ratio of end-of-life module remanufacturing $\beta = 80\%$, so that 15% of end-of-life modules are shipped from recycling centre nodes directly to the e-waste treatment facility for disposal, and another 17% of end-of-life modules are shipped from the remanufacturing centre to the waste treatment facility. Secondly, this paper assumes that in the PV manufacturer's recycling scheme, all end-of-life PV modules are recycled, $\tau = 100\%$, the dismantling ratio of the PV manufacturer is also $\alpha = 85\%$, and the remanufacturing ratio of the manufacturer is also $\beta = 80\%$, and the rest of the 15% end-of-life modules are disposed of by the PV manufacturer itself.

4. DATA ANALYSIS

The mixed integer linear programming model, i.e. the MILP model, is used in this study, and we solve this model using the CPLEX solver, which was developed by the ILOG division of IBM, and is widely used for mathematical optimization problems in mixed integer programming. The CPLEX solver is characterized by its high performance and flexibility, and is able to solve many complex optimization problems, thus In this paper, CPLEX is used to find the optimal solution, including the siting scheme of the recycling centre in the reverse logistics network of photovoltaic recycling. In this paper, CPLEX software was used to write a programme to solve the two models presented in this paper and the models were tested using three scenarios. The first model is used to solve the government recycling scheme and the WEEE recycling scheme, and the second model is used to solve the PV manufacturer recycling scheme. In this study, the end-of-life volume of PV waste modules in each city of Zhejiang Province in 2035 is selected as the data for the study, and the

minimized cost of reverse logistics is obtained by using CPLEX solver as In the optimal solution obtained.

4.1. Analysis of the government recovery programme

In Scenario 1, the locations of the facilities in the end-of-life module recycling network in Zhejiang Province are as follows: (1) Recycling centre: one each in Jiaxing City, Huzhou City, Lishui City, Hangzhou City, Ningbo City, Wenzhou City, Shaoxing City, Jinhua City, Quzhou City, Zhoushan City and Taizhou City; (2) Disassembly and processing centre: one each in Jiaxing City, Huzhou City, Lishui City, Hangzhou City, Ningbo City, Wenzhou City, Shaoxing City, Jinhua City, Quzhou City, Zhoushan City and Taizhou City; (3) Remanufacturing centre: Zhejiang Astronergy Development Company Limited, Zhejiang Baolite New Energy Co. Ltd, Zhejiang Chint New Energy Development Co., Zhejiang Baolite New Energy Co. Ltd, Zhejiang Ruishang Energy Technology Co., Ltd, Zhejiang Tongjing New Energy Group Co., Ltd; (4) Waste treatment institutions: in Hangzhou Dadi Ocean Environmental Protection Co. Ltd., Shaoxing Xinjie Environmental Protection Technology Co., Ltd., Zhejiang Juhua Environmental Protection Technology Co., Ltd., Zhejiang Greenchen Environmental Protection Technology Co., Ltd., Huzhou Yihuan Environmental Protection Technology Co., Ltd., Zhoushan Liancheng Environmental Protection Technology Co., Ltd., Dongyang Nahai Environmental Technology Co., Ltd., Zhejiang Shuo Bo Renewable Resources Co.

4.2. WEEE recycling plant programme analysis

In Scenario 2, the locations of the facilities in the recycling network for end-of-life components in Zhejiang Province are as follows: (1) Recycling centre: one each in Zhejiang Shengtang Environmental Protection Technology Co. Wenzhou, Shaoxing, Jinhua, Quzhou, Zhoushan and Taizhou; (3) Remanufacturing Centre: Zhejiang Chint New Energy Development Co. Ltd, Zhejiang Kaiying New Material Co., Ltd, Zhejiang Ruishang Energy Technology Co., Ltd, Zhejiang Tongjing New Energy Group Co. Ltd., Wenzhou Clean Energy Renewable Resources Co. Ltd., Taizhou Dechang Environmental Protection Co.

4.3. Analysis of photovoltaic manufacturer programme

In Scenario 3, the locations of the facilities in the recycling network for end-of-life modules in Zhejiang Province are as follows: (1) Recycling centres: one each in Zhejiang Chint New Energy Development Co. Ltd, Zhejiang Ruishang Energy Technology Co., Ltd, Zhejiang Tongjing New Energy Group Co. Ltd, Wenzhou Clean Energy Renewable Resources Co., Shaoxing Xinjie Environmental Protection Technology Co. Ltd.

5. CONCLUSION

Nowadays, China's photovoltaic power generation industry is developing rapidly, and it is expected that the wave of PV end-of-life will come in the future when the service life of PV modules expires, so the recycling and treatment of end-of-life modules will become a big problem. At present, foreign countries such as the European Union, the United States, and others countries have introduced relevant recycling policies to promote the effective recycling of end-of-life PV modules, due to the late start of China's photovoltaic industry, has not yet formed a large-scale module scrapping, and at the same time, China's government for the photovoltaic end-of-life treatment is still in the blank stage and has not introduced relevant policies, so there is an urgent need to plan a reasonable and effective end-of-life module reverse recycling network system. Therefore, there is an urgent need to plan a reasonable and effective reverse logistics recycling network system for end-of-life photovoltaic modules, which is used for the recycling of end-of-life photovoltaic modules, and promotes the protection of the environment and the sustainable development of resources, and great significance

for the optimization of the layout of the reverse logistics infrastructure. In summary, according to the principle of Extended Producer Responsibility (EPR principle), this paper considers the siting strategies of three stakeholders related to the PV industry, which are government recycling, WEEE recycling, and PV manufacturer recycling, and conducts an in-depth study on the planning of end-of-life module recycling network according to the three recycling schemes, and the difference of the three schemes lies in the impacts of different recycling center nodes of the constituency on the total cost of reverse logistics, taking Zhejiang Province as an example. The impact of the three scenarios lies in the influence of the different recycling center nodes on the total cost of reverse logistics, the optimization of the PV end-of-life module recycling network, and the siting of the recycling infrastructure through the MILP model in Zhejiang Province. The research in this paper still has some limitations, China's PV module end-of-life is still in the embryonic stage, in the field of PV module reverse logistics research-related data is relatively small, and a lot of data rely on the map to find and predict the data generated, so the accuracy of the data in this study is still to be improved. Secondly, in this paper, in the design of the model of the end-of-life module reverse recycling network, problems such as multi-batch transport are not considered, and the subsequent research needs further improvement. Meanwhile, this study only considered a single PV module and only took Zhejiang Province as the research object, future research should consider the multi-product recycling program, which can take the Yangtze River Delta region, Pearl River Delta region, Beijing, Tianjin, and Hebei regions as the research object, and combine the separate recycling and cooperative recycling of carbon and silicon modules and thin-film modules in PV modules.

Based on the results of this study, it is recommended that the state and the government formulate a clear PV recycling policy in the future and that the state should carry out macro-control and formulate relevant incentives to promote the active participation of PV enterprises, which will be conducive to the promotion of the network construction of PV reverse logistics recycling. In the future, strengthening industry cooperation or cross-industry cooperation, and the introduction of relevant laws and regulations by the state can just solve the difficulties faced by the PV industry in the future, promote sustainable development, and improve economic efficiency.

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