Circular Solutions: Assessing the Viability of Photovoltaic Waste Recycling in the United Kingdom

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Abstract—**The demand for the generation of energy using photovoltaics (PV) has risen exponentially in recent times all over the world. The United Kingdom (UK) has also made a rapid increase in PV installations and is implementing more developing plans in the future as it is focusing on generating significant amount of electricity using photovoltaics. These PV installations will become waste in future. Hence, it is important to plan the end-of-life management of PV waste. This paper gives an insight into the current and future scenarios of PV waste recycling in the UK with literature reviews, discussions on recycling methods and cost benefit analysis. It shows a projection of PV waste in future, by exploring the installation of a recycling facility based on Full Recovery End of Life Photovoltaic (FRELP) method of recycling in Cornwall, UK. From the analysis, it was calculated that the recycling facility could generate total yearly revenue of £5,852,745.80 approximately with a profit of £92,435.14.**

Keywords—**photovoltaic, photovoltaic waste, cost-benefit analysis**

I. Introduction

Solar power generation has emerged as a principal solution to reduce climate change in past years [1]. The growth of photovoltaic (PV) modules is a positive element as it indicates that the world is shifting its focus towards environmental sustainability and renewable energy resources. Also, the price of solar panels has lowered by 80% in the last 10 years [2]. Official statistics indicate that around 1.5 million rooftop solar systems were installed on UK homes [1]. Additionally, there are roughly 1,170 solar farms in operation in the UK [1]. There were new additions of solar installations in 2023 with capacity 1.1 GW in the UK which was 6.8% higher than in 2022 [3], and it is estimated that the total solar capacity of the UK will reach 70 GW by 2035 [4].

However, there are some negative aspects associated with the growth of PV modules. The number of PV modules is increasing day by day and they are generating wastage at the end of their life cycles. With increasing solar installations in the UK, the necessary plans for end of life (EoL) management need to be implemented. The UK is estimated to have 30,000 tonnes of PV waste in next 10 years [5]. Furthermore, IRENA and IEA estimate the total PV waste all over the world could reach 78 million tonnes by 2050 [6], as illustrated in Fig. 1. This will also result in lack of raw material supply used to manufacture solar panels [5].

The worldwide solar PV installation has extended up to 942 GW by 2021 and has been rising rapidly [7]. However, only 10% of PV waste is being recycled worldwide and the rest goes to landfill [8]. This is very harmful to the environment as it contains toxic materials [8]. With the rising of solar installations all over the world, the flow of PV waste will also rise subsequently. The PV modules contain expensive and rare earth metals which can be obtained through recycling PV waste yet recycling processes remain relatively unexplored. The principal reasons have been a lack of research, difficulty in recycling and not enough commercial methods available for recycling. Currently, the policies and required regulations to manage the EoL PV modules have only been implemented by the European Union.

It has been highlighted by El-Khawad *et al.* [9], that crystalline silicon (c-Si) solar panels were the first-generation solar panels presiding the world market since 1990s. These solar panels still account for 95% of overall global production. The dominance of c-Si panel is estimated to decline up to 44.8% by 2030 while the latest generation PV panels are expected to rise up to 44.1% from overall current market share of 1% [10]. Fig. 2 shows the components of a solar panel. Presently, there are two ways of recycling PV panels which are industrially recognized. The largest market share is acquired by c-Si panels and the second dominance is of CdTe or CIGS panels. Both need different recycling approaches.

According to Mulazzani *et al.* [7], the EoL of panels occurs due to three causes during their operating life which are failure during early stage of installation, failure after some years of working cycle and failure at the end of working cycle. The European Waste Electrical and Electronic Equipment (WEEE) directive 2012/19/EU put into practice extended producer responsibility (EPR) which obliges manufacturers manage EoL PV modules.

The current recycling approaches as well as technologies are based on silicon-based modules and these modules do not have sufficient valuable materials to recover [11]. The cost of the recycling techniques is comparatively higher than the landfill option. However, the recycling of solar PV modules can increase the sustainability related characteristics on a long-term basis. The researchers and PV industry are working continuously to identify cost effective materials and efficient methods for manufacturing solar PV modules and specific approaches to keep them bonded for multiple years of outdoor exposure. It is important to note that appropriate regulation has the potential to increase the overall characteristics related to the recycling process. On the other hand, the recycling method is not a cost-effective approach, and it is the main problem statement in this case. Accurate cost estimation in relation to the benefits of PV waste recycling can offer precise guidance. Different components make up a solar panel, each requiring specific recycling procedures to ensure the proper handling of PV waste. However, it requires a complicated and strong AI based mechanism and systems that ultimately provides different elements from the solar panels.

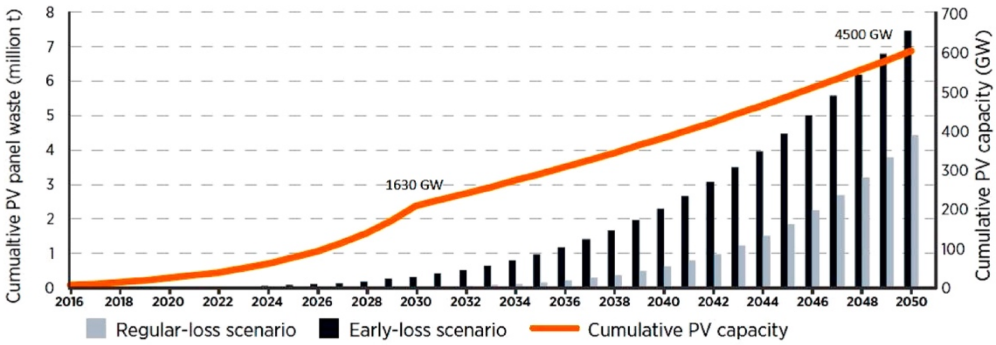

Fig. 1. Approximate growth of global PV waste (tonnes) 2016-2050 [10].

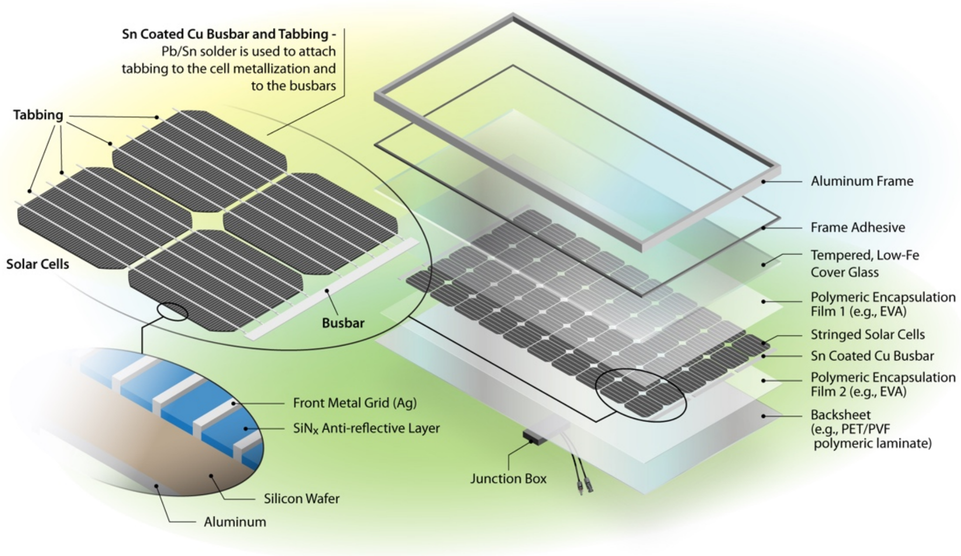

Fig. 2. Components of a solar panel [12].

This paper examines PV waste recycling in the UK, employing the Full Recovery End of Life Photovoltaic (FRELP) method to offer insights into operational costs and potential revenue. It examines the recycling methodologies, conducts cost-benefit analyzes, and forecasts PV waste trends. Additionally, it proposes the installation of a recycling facility, accompanied by financial projections. The findings hold promise for encouraging both individuals and businesses to embrace PV waste recycling in the UK, promoting economic growth at both micro and macro levels. Furthermore, the cost-benefit analysis aids policymakers in gauging the economic viability of recycling methods, empowering government and private entities to implement tailored strategies based on the research's key insights.

II. Literature Review

A. Methods of Recycling PV Waste

Majewski *et al.* [13] stated that by looking at the current scenario, in the next 25-30 years there will be tonnes of PV waste all over the world. It was noticed that the worldwide waste will keep increasing only unless immediate actions are taken. There is no prominent method to recycle the PV waste efficiently. The current situation is critical as only copper wires are currently being recycled from PV panels, while plastic materials require combustion for disposal. This results in emission of toxic gases which are hazardous to the environment. PV waste recycling is not only beneficial to the environment, but it also has economic potential to create value.

There are a variety of methods for recycling PV waste. The efficiency of these technologies is determined by a variety of criteria, including the kind of PV waste, the purity of the recovered components, and the environmental impact of the recycling process. PV modules are recycled in the three stages of delaminating, objects separation and purification of the materials recovered. The process works by removing junction box, wires and frames that can be easily dismantled. After dismantling, the modules go for separation under physical, chemical and thermal recycling methods. Over 94% of materials are possible to recover today under different separation model.

Recycling of complex materials is costly which are done through thermal and chemical separation process and most of the recycling acts end during physical separation only. Apart from that PV module contains silver and copper in low quantity which most of the private entities get interested in. However, less parties show interest in removal of glass or lead materials which are complex and have low market price at present.

B. Physical Recycling

Mechanical separation is the use of mechanical techniques to separate PV waste into its component elements, such as grinding, shredding, and screening. Mechanical separation process can be turned as the physical recycling process through which ultimate shading of the photovoltaic cells occurs and they are required for recycling purposes [14]. Mechanical separation mainly occurs through the utilisation of modern and advanced AI oriented machines.

After complete shredding of the PV solar cells the actual elements like glass, silicon powder, plastic, delaminate glass cells can be gathered. Physical recycling technologies are successful for recovering silicon and aluminium; on the contrary there have been certain complications which are associated with lack of purity after the development of PV waste [15]. However, with time it can be identified that complications associated with the purity issue can be solved by the organisations through the development more efficient and powerful machineries.

C. Chemical Recycling

Chemical treatment of silicon-based PV cells is also an interesting process as through this procedure pure silicon can be recovered that is embedded under different layers of materials under the photovoltaic cell. Through the chemical process of recycling, the solar panel is taken under different chemicals which includes KOH solution, water, etching solution and then again on water (see Fig. 3).

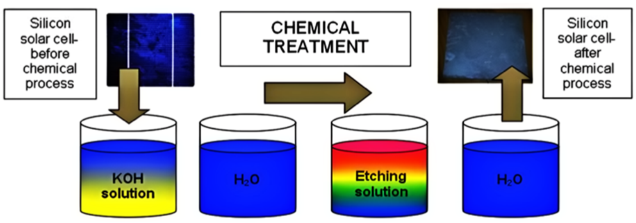

Fig. 3. Chemical recycling procedure for PV cells [16].

By passing these elements through these two chemicals, pure silicon can be extracted after the overall chemical procedure. However, there has been a complication which is choosing the proper composition of itching solution for its concentration as it is related to optimal process temperature. Apart from that, the quantity of the silicon that is attained after the procedure is far less compared to the physical process.

Most of the methods related to recycling of PV are subject of laboratory-based research works. However, recently two commercially available methods are in this sector. For instance, one US-based solar manufacturer has applied both chemical as well as mechanical treatment methods in the context of thin film solar panels. c-Si solar-panel has been applied by a Germany-based organisation and China has a limited facility regarding the recycling method of component repair as well as panel separation. China-based organisations generally hire external technology teams to conduct the recycling as well as separation of different individual materials. Most of the developing countries face issues with introducing recycling technology like mechanical or physical approaches. Generally, it generates a comparatively higher amount of dust and it contains glass. The processes are toxic and tend to generate large amounts of noise pollution. For instance, the separation related to the EVA layer through inorganic solvents can lead to the emission of nitrogen oxide as well as other harmful gases. The emissions are related to health-related risks and the approach related to re-utilizing the silicon wafers within the frame. Removal is a difficult approach for disposing of the remaining liquid. It has been highlighted by Padoan *et al.* [17], that the required time for EVA solution through familiar organic solvents can be long and it can be improved through the utilisation of ultrasound. However, this approach is a method for generating larger amounts of organic melted wastage and it is a difficult approach to treatment. The combination of chemical and thermal methods is categorized as an advanced technology-based approach. However, there are certain limitations associated with this approach as it consumes much higher amounts of energy and it produces toxic gases which are not good for the environment.

The chemical recycling approach is considered as one of the most advanced as well as technology-based approaches, but it has multiple limitations. It is a costly method and developing countries may face difficulties organizing the required energy consumed by the chemical recycling process. Handling the produced toxic gases is another crucial task for the businesses or the countries. According to Farrell *et al.* [18], wet-chemical extraction related to metals from CIGS panels can be a difficult as well as costly approach. For instance, the overall success rate of this method is highly dependent on desalination of composite and recovering the Cu and separating different metals like Ga and In. It is considered one of the most energy consumable approaches and the increased cost related to this method can reduce the chances of the business organisations or the countries to adopt this strategy. However, proper investment in the sector is required to identify as well as introduce the most cost-effective and environmentally effective approaches.

D. Thermal Recycling

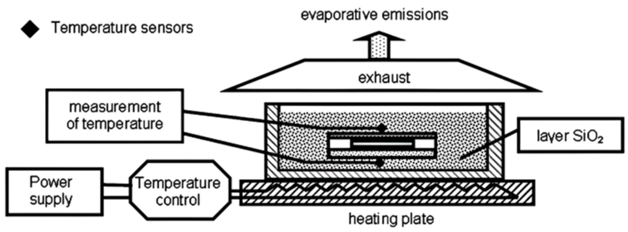

Fig. 4. Thermal sensing process of PV cells [16].

Fig. 4 shows the thermal sensing process of PV cells [16]. In order to separate the silicon photovoltaic cells from the damaged PV modules the solar panels are placed in a SiO_2 bed that is heated to an increased temperature for a certain amount of time based on which residual materials are generated after thermal treatment. In comparison to the chemical recycling treatment the thermal treatment is far faster and involves less problems as the individuals engaged in the treatment process are not exposed to harsh chemicals that are problematic for their health [19]. On the contrary, the thermal process has certain complications which are mainly the emission of gases during the EVA polymer thermal degradation procedure however this process is simple and highly efficient and can be used widely in PV recycling installations mainly in the commercial sector. This method is far superior compared to the chemical treatment as the thermal treatment is far more convenient and less energy consuming resulting in degradation in cost management and providing good quantity of PV waste compared to chemical treatment.

E. Effectiveness of Recycling PV Waste

The effects of recovered PV waste can be both beneficial and harmful, depending on the recycling processes employed and how the trash is disposed of after recycling. Positive impacts include minimizing the amount of garbage disposed of in landfills, conserving scarce resources, and lowering the environmental impact of waste disposal. The release of harmful chemicals into the environment, the production of greenhouse gases, and the potential harm to human health and the ecosystem are all negative impacts [20]. To guarantee that recycling is done in an ecologically friendly way, it is critical to thoroughly assess and minimize the potential harmful consequences of recovered PV waste. The efficacy of recycled PV waste is determined by a variety of criteria, including the recycling method employed, the quality of the recovered materials, and the eventual use of the recycled materials. Mechanical recycling procedures, such as disassembly and separation, are often less energy-intensive and cost-effective than chemical processes, such as solvent dissolving. On the other hand, mechanical procedures may not be able to recover materials of the same purity as chemical processes, which might have an impact on the quality of the recovered materials. Physical recycling technologies are successful for recovering silicon and aluminium, but they have limitations in terms of the purity of the recovered materials and the quantity of energy required for the recycling process.

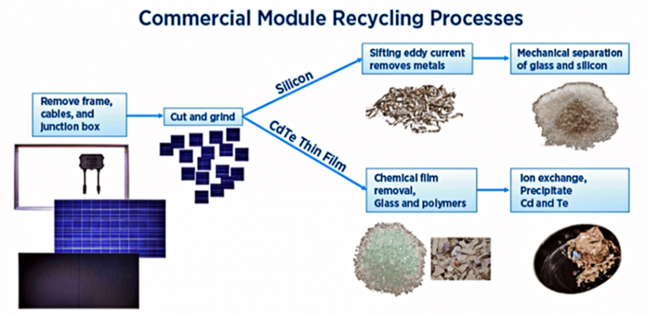

Fig. 5. Commercial module recycling process [21].

Fig. 5 shows the commercial module recycling process. Chemical recycling technologies are successful for recovering high-purity silicon, but they are costly and have environmental consequences due to the use of hazardous solvents and acids. The subsequent use of recovered materials is also critical in determining the efficacy of recycled PV waste. Recycled materials may be utilised to make new PV panels, construction materials, and energy storage devices, among other things. The use of recycled materials in these applications can have considerable environmental and economic benefits since it decreases the demand for new raw materials and the greenhouse gas emissions associated with their manufacturing. Thermal recycling technologies can be efficient for lowering the volume of PV waste, but they have limits in terms of environmental impact and material recovery. The efficacy of recycled PV waste is also determined by the quality of the recovered components. High-purity materials, including silicon and aluminium, may be employed in the manufacture of new PV panels, reducing the requirement for new raw materials [10]. Low-purity materials, on the other hand, may have restricted applications, such as the manufacture of poorer-quality PV panels, which can result in a lower cost benefit. In the future, as the PV industry expands, recycling of PV waste is likely to become increasingly essential. With the rising need for sustainable energy sources, the PV sector is likely to develop further, resulting in an increased volume of PV waste. Recycling PV waste will be critical in controlling this waste and decreasing its environmental effect, while also delivering economic advantages through the recovery of valuable materials. The thermal impacts of recovered PV waste might vary depending on the recycling technologies employed and how the trash is disposed of after the process.

Fig. 6 shows the materials in a typical silicon PV cell. At present, there is no such infrastructure on a mass level present to face the challenges from PV waste that are going to rise once the shelf life ends [22]. Removal of the aluminium frame and the electrical circuit box is the easier part and most of the recycling process stops there. However, it is crucial to separate silver and other metals before sending the dismantled parts to a landfill. Apart from that higher demand for metals with limited availability is bringing challenges to the mass production of PV modules. It is crucial to understand that silver, silicon and copper constitute two third of the module value which means inability to dismantle will lead to the waste of precious metals that will become harder to procure as time goes on. One of the key challenges remains to separate a module glass from the cells. Application of organic solvents to eliminate EVA is possible, however, the process is highly expensive and there is a risk of hazardous waste production. Apart from that there are recyclers applying infrared heaters as knives to separate panel glass away which is an expensive set-up difficult to apply without proper support from the government [22].

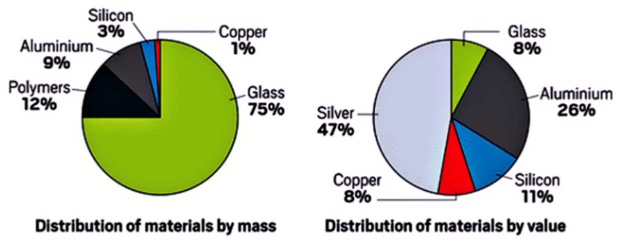

Fig. 6. Materials in typical silicon PV cell [22].

F. Environmental impacts of PV waste

Solar panels contain different elements such as Cd, Pb, Sn, In and Se which on direct dumping to the ground can react and prove hazardous to air and water. According to Tawalbeh *et al.* [23], the presence of toxic elements during panel construction, though they do not have much impact during the operational phase, can prove dangerous if negligence in the recycling process occurs.

Rabaia *et al.* [24] stated that, PV waste is of great concern to the life and health of living creatures on the planet. Special care is required during the disposal and end life management of these cells. Direct dumping is the least preferred option as most of the materials used in the manufacturing are reactive which can release harmful gas or concentrated acids if exposed. Furthermore, the recycling process includes shredding, detaching, solubilizing and chemical bath where direct drainage of wastewater is hazardous. Materials which cannot be reused should be dumped into a land far from the habitant areas to prevent piling of waste materials. It is crucial to understand that open dumping is not a solution and so research on the use of materials that are non-reactive to nature is prominent in today's time. In addition to promoting the commercialization of solar photovoltaic cells for renewable and clean energy, establishing recycling facilities is essential.

There is an opportunity present in PV waste management where companies can earn through materials in use for reuse and repair. Future PV waste market is expected to rise as EoL for most of the PV's is going to complete by 2030 for which new dismantling facilities will be sprung. Proper planning will allow channelizing economic benefits where recycling entities can bid for waste contracts. Tenders to dismantle the whole structure or part can be given depending on the type of usage. It is assumed that waste management for large utility scale PV applications is logistically easier, although dismantling depends on the type of construction. Similarly cost attached to dismantle smaller PV units depends on the type and location. As of now PV waste quantity is not sufficient to set dedicated recycling units taken into consideration of global waste market. At present most of the recycling plants are dwelling with PV panels where reuse of the materials is the main focus. There is a necessity for skilled workforce to avoid any damage to PV panels. Raw material extraction from PV waste is going to become a bigger market in future, owing to scarcity and high price of raw materials. A PV panel is going to build a large pile of waste stock in coming years. Greater value can be created if raw materials are properly extracted.

EoL of PV waste management is expected to gain growth in coming future as dependency to clean and green energy is rising. Solar photovoltaic cells are an easy solution to the green energy demand. Recent commercialization of PV solar panels has allowed many new and global entrepreneurs to jump into the solar energy business [25]. Although at present large-scale recycling of thin PV panels is still at early stages where most of the entities are configuring on ways to bring out economy from PV waste. Recent research advancements in the treatment of waste volumes have brought hope in the market. For instance, recycling of thin films is processing of chemical and mechanical treatments. One of the technical challenges in PV recycling is the delaminating or the removal of the encapsulate material.

At present 65 to 70% raw materials are possible to extract which is expected to grow with advancement in technology [26]. Advancement in research has allowed producing cheaper solar panels with thin films and high reduction over use of materials. C-Si PVs continue to dominate the solar market in which Silicon is prominent material in use. This means future market for recovery of Silicon is higher along with silver which is the next valuable material use in the construction of panel. It is vital to understand that some materials are hard to recover today such as sealants and polymers but with advancements in recovery research the potential to unlock is higher. EoL PV panels have high potential to generate jobs in both public and private sectors in which government can come up with waste tenders and research programmed. On the other hand, private entities can enter into the business of reselling used and recyclable materials. Employment in the section of waste transportation, disassembling, dismantling, treatment and research is present for which essential steps from now needed to be taken on global front. According to Gangwa*r et al.* [27], it is crucial to prepare for the emerging market having necessity skills and knowledge of recycling process to uphold 3R circular economy. There are three businesses that can spurge through PV waste; the first is R&D organizations, which will work on innovations in the sector of production and waste management. The second is repair or reuse service business in which collection and refurbishing of parts is there and the third is recycling and treatment business.

G. Barriers Associated with PV Waste Recycling

PV waste recycling is a complex process as solar modules contain different types of materials such as rare earth metals and silicon. The UK is one of the diverse and highly working countries with rapid growth of industrialization and urbanization. As a vast number of industries have focused on the recycling technique to manage waste, the UK is facing significant problems in handling PV wastes. The lack of regulations concerning the recycling of solar panels is a concern for manufacturers, as it fails to incentivize the proper disposal and recycling of PV modules. Due to the absence of proper regulation in the UK government, the recycling technologies used for PV waste disposal are inefficient and rarely deployed.

III. Methodology

A. Choice of Method and Location of Recycling PV Waste

It is necessary to mention that the most suitable process of the 3 recycling procedures has been the mechanical procedure based on the physical recycling process as it is fast and provides an increased amount of PV waste. Apart from that, important elements like glass silicon powder, plastic, de-laminate glass sales and other important elements are gathered in separate areas for better utilisation of the waste materials in future. On the other hand, the chemical procedure is less suitable as the rate of collection of PV waste is very low and only the fragments of damaged PV or fragments of tedlar and glass or ribbons are found from the chemical waste generation [16]. Apart from that, thermal procedure is better compared to the chemical process as it provides more recyclable elements however it cannot be utilised in large scale due to its increased gas emission. Based on this evaluation, it can be identified that the physical recycling procedure is be best suited for the recycling as it is a faster and more cost-effective process compared to the other processes. Due to this reason, it is highly necessary for organisations to choose the physical recycling process and implement better AI based technology through which better recyclable elements can be attained through this procedure. Machines like Solar 4.0 [28] have been beneficial in mechanical separation and physical recycling procedure as it is a faster and more convenient process compared to other forms of PV recycling.

The location selected for installing PV waste recycling facility was Cornwall, which is located in the South-West part of England in the UK. Cornwall was selected for the installation of recycling infrastructure, because it is the prime location for solar installation in the UK. There are a total of 183,015 renewable energy sites in the south-west, and roughly 13% are in Cornwall [1]. Also, due to the favourable weather conditions for solar installations, it is likely to have more future solar panel installations in Cornwall [1]. Another reason behind selecting Cornwall was that when most the current solar installations will reach their end of life, the distance between recycling facility and solar sites will be less. It was evident from the cost benefit analysis that the transportation cost of PV waste from site to recycling facility was the most significant cost component from the total recycling cost. Hence, the transportation cost will be greatly reduced which will result in increased profits.

B. Cost Benefit Analysis of Recycling PV Waste

1) Decommissioning cost of panels

Decommissioning is the method of dismantling end of life solar panels and clearing that land area for further use [29]. The steps to be followed are dismantling of infrastructure, management of removed components and ensuring that, the land is in the state of further use for development. The decommissioning expenses depend on size of the site, location and complexity. Table 1 demonstrates the approximate expenses of decommissioning for a ground mounted 2 MW solar panel system.

Table 1. Decommissioning tasks and estimated expenses for a ground mounted 2 MW PV system [29]

Task	Cost (£)
Remove Rack Wiring	1,971.50
Remove Panels	1,964.29
Dismantle Racks	9,901.61
Remove Electrical Equipment	1,483.24
Breakup and Remove Concrete Pads or Ballasts	1,202.63
Remove Racks	6,253.65
Remove Cable	5,211.38
Remove Ground Screws and Power Poles	11,104.24
Remove Fence	3,968.66
Grading	3207.00
Seed Disturbed Areas	200.44
Truck to Recycling Center	1,803.94
Current Total	48,265.35
Total After 20 Years (2.5% inflation rate)	79,293.07

2) Estimated expenses in PV waste recycling

According to Markert *et al.* [15], Full Recovery End of Life Photovoltaic (FRELP) process of PV waste recycling was developed for large scale commercial recycling. This paper will focus on estimating overall expenses associated with this process. Fig. 7 shows the expenses required at various steps in the FRELP process.

The basic unit used in this study is 1 m^2 of PV. Total expense of PV recycling is given by the following formula:

$$Total\ Expense = \sum Private\ Cost + \sum External\ Cost - \sum Benefits \quad (1)$$

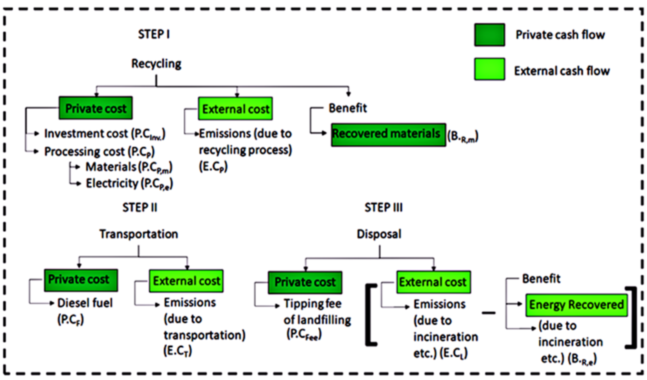

Fig. 7. Framework in analyzing the cost of FRELP recycling method [15].

The private cost is the expenses a PV recycler must do during EoL management of PV waste. This includes expenses for buying machines, expenses on materials and expenses on electricity required to run the machines. It also includes the expenses on fuel required for transportation of PV waste from site to recycling facility and the amount paid to dump unrecovered materials.

$$\text{Private Cost} = P.C_{Inv} + P.C_{P,m} + P.C_{P,e} + P.C_F + P.C_{Fee} \quad (2)$$

The external cost is the values referring to the damage to the environment due to toxic gases emitted during recycling process, transportation and combustion while dumping.

$$\text{External Cost} = E.C_P + E.C_T + E.C_L \quad (3)$$

The benefits are the profits from recovered materials.

$$\text{Benefits} = B._{R,e} + B._{R,m} \quad (4)$$

3) Actual expenses in PV waste recycling

Markert *et al.* [15] has carried out a detail analysis on the actual expenses in PV waste recycling for 1 m^2 c-Si PV module. The total EoL cost of 1 m^2 of c-Si PV module was found to be £5.36/m^2. From all the cost elements of PV EoL management, the transportation cost was maximum (£2.68/m^2) while the expenses of the recycling process were found to be the lowest (£0.20/m^2). The principal cause for the high transportation expense was due to the long distance of transportation required in the end-of-use of PV panels.

Their analysis indicated that the electricity required is the most expensive cost element of the PV recycling process. It was observed that the total external expense of PV EoL management is approximately £4.54/m^2. The PV recycling process makes up the majority of the external costs (£3.25/m^2). Transportation and land filling both accounts for 19% of the total external expenses of PV EoL management.

The commercial profit of recovered materials with FRELP process was found to be £10.84/m^2. It can be concluded that the net commercial profit of £5.58 can be generated by recycling 1 m^2 of c-Si PV waste using FRELP method.

The total cost of c-Si recycling, including both private and external costs, is £9.91 without considering the benefit from recovered materials. When the profit from recovered materials is added, the profit is £0.95. The total cost of PV recycling we found is £0.95/m^2, meaning that it is cheaper to recycle and use PV panels made from recycled materials.

IV. Result and Discussion

A. Projection of PV Waste in the UK

According to Mahmoudi *et al.* [30], solar PV panels have a life of 25-30 years. The number of panels reaching their EoL is increasing globally. Also, looking at the pace at which the solar installations are being done currently, the quantity of panels reaching their end of life in near future will rise significantly. It was projected that the PV waste would be 1.7–8 million tonnes by 2030 and 60-80 million tonnes by 2050 [6]. The total amount of installed solar PV capacity (MW) every year in the UK by the end of 2021 is 13,965 MW.

Considering the PV waste collected by WEEE during the period from 2015 to 2021 and taking the average of the total PV waste collected during that period, it was found that the average quantity of PV waste collected per year was 134.6 metric tonnes. From this, it was estimated that the amount of PV waste collected each year would be increasing at 7.5%

every year approximately in the future. Fig. 8 shows the estimation of PV waste in the UK until 2050.

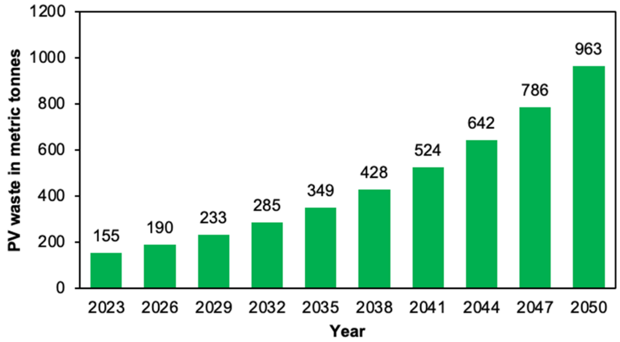

Fig. 8. Estimated collection of PV waste in UK.

B. Location of Recycling Facility in UK

As discussed in the Methodology section, Cornwall was selected as the optimum location to create the PV waste recycling facilities due to its many advantages mentioned previously.

C. Financial Analysis of PV Recycling in Cornwall

Based on the study by Mulazzani *et al.* [7], the capital investment required to setup recycling facility based on FRELP method of recycling was approximately £4,429,468.91. According to Latunussa *et al.* [31], this recycling plant had capacity of one tonne/hour and was sufficient to recycle PV waste of 8,000 tonne/year.

The financial analysis rests on the information gathered from FRELP PV recycling process study. The industrial land costs approximately £8,000 per acre in Cornwall and nearby areas [32]. The purchase of 250 acres of industrial land for the recycling plant infrastructure, costing £2 million, will involve a 40% upfront payment as a deposit, with the remaining 60% assumed to be financed through a loan at a 5% interest rate. The rest of the amount was utilised for financing equipment, machineries, construction, utilities, camera installation, licensing, internet installation, etc. Table 2 depicts the operational expenses for recycling one tonne of PV waste in an hour.

Table 2. Decommissioning tasks and estimated expenses for a ground mounted 2 MW PV system [29]

Input / Output	Quantity	Expense (£)	Total (£)	Ref.
Electricity (kWh)	113.55	0.36/kWh	408.78	[33]
Fuel (kg)	1.14	2.06/kg	2.35	[34]
Water (kg)	309.71	0.002/kg	0.62	[35]
Nitric acid (kg)	7.08	10.2/kg	72.22	[36]
Calcium hydroxide (kg)	36.5	7.75/kg	282.87	[37]
NOx (kg)	2.00	-	-	
Landfill waste (kg)	320.13	0.2/kg	64.03	[38]
Toxic waste (kg)	52.25	0.6/kg	31.35	[39]
TOTAL			494.32	

Assuming that 20 labourers were required for the daily operation of the plant working in two 12-hour shifts with 10 labourers in each shift and a recycling capacity of 22 tonnes/day, the hourly pay rate for the labourers was £9.50/hour for each [40]. The salary expense on labour was calculated to be £103.64/tonne. Assuming the loading capacity of a truck as 20 tonnes, the total loads of PV waste were 401.5 trucks per year and assuming the transport cost was £40/tonne including the addition of 2 labourers and fuel expenses.

The recycling plant can be considered as a large business and the total annual consumption of gas of large businesses in the UK was on average 75,000 kWh per year [41]. The total expenses of the plant in a year is shown in the Table 3. The salary of the staff was assumed £15.00/hour working 40 hours/week. The average cost of business insurance per year was £118 [42].

The calculation of revenue from the recycling of one tonne of PV waste obtained by the market value of recovered materials is as shown in Table 4. Assuming that the plant was running at its full capacity, which was 8,030 tonnes/year, the total revenue/year was £5,852,745.8.

Table 3. Total expenses/year of the plant

Input / Output	Quantity	Expense (£)	Total (£)	Ref.
Electricity (kWh)	911,806.50	0.36/kWh	328,250.34	[33]
Electricity standing charge (day)	365.00	1.38/day	503.70	[33]
Gas standing charge (day)	365.00	2.78/day	1,014.70	[33]
Gas (kWh)	75,000.00	0.10/kWh	7,500.00	[33]
Labour salary (hrs/day)	240.00	9.5/hr	832,000.00	[40]
Staff salary (hrs/week)	40.00	15/hr	144,000.00	
Transportation (truck loads)	401.50	40/tonne	321,200.00	
Loan installment (£1.2 million)	5.00%	12,727.86/month	152,734.32	
Internet bill	-	64/ month	768.00	[43]
Business insurance (number of employees)	25	118/year	2,950.00	[42]
Operational expenses	8,030 tonnes	494.32/tonne	3,969,389.60	
Total			5,760,310.66	

Table 4. Revenue from recycling of 1 tonne PV waste

Recovered material	Quantity (kg)	Market value (£/kg)	Total (£)	Ref.
Glass	686.00	0.02	13.72	[44]
Copper	4.38	4.23	18.53	[45]
Aluminium	182.65	0.88	160.73	[45]
Silicon	34.68	7.09	245.88	[46]
Silver	0.50	580.00	290.00	[47]
Total			728.86	

D. Cash Flow Projection

From the analysis, it was calculated that the total operational expenses of the plant in a year was £5,760,310.66. From the calculation of revenue obtained by the market value of recovered materials, it was observed that the recycling facility could generate total yearly revenue of £5,852,745.80 approximately. It can be concluded from the analysis that the plant will generate a profit of £92,435.14. This gives an ROI of approximately 2%. The profits can fluctuate at the end of the year as it depends on the variable expenses on transport and fluctuations in the prices of recovered metals.

Considering an inflation rate of 4% every year until 2053, the estimated total expenses and total revenue of the recycling plant as shown in Fig. 9, achieving a total revenue of £18,982,781.15.

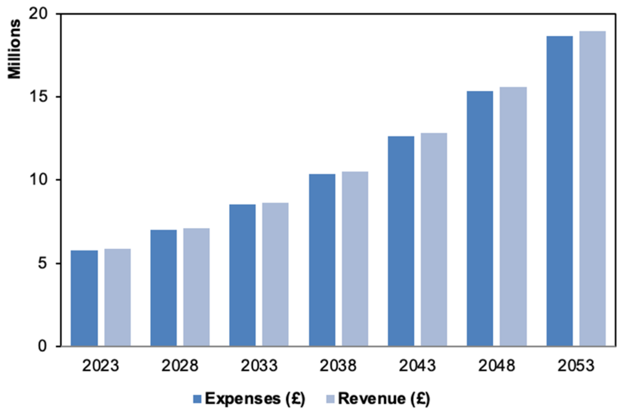

Fig. 9. Projection of total expenses and revenue of the recycling PV plant.

Analyzing the cash flow projection for income in PV recycling reveals significant practical implications. The positive cash flow projection indicates potential profitability and financial stability linked to investments in PV recycling initiatives. This insight is vital for stakeholders and decision-makers, suggesting that dedicating resources to PV recycling could result in substantial returns over time. Moreover, understanding the cash flow dynamics aids in strategic planning and budgeting. It facilitates effective financial resource management and strengthens the feasibility of achieving long-term sustainability goals. Integrating these insights into planning processes enables informed decision-making that supports environmental conservation and promotes economic growth within the renewable energy sector.

Increasing revenue in PV recycling generally involves two main strategies: enhancing revenue from recovered materials and reducing costs [48]. To increase revenue from recovered materials, improvements in technology and the recycling process are essential. These advancements can lead to higher efficiency in extracting valuable materials from solar panels, thereby increasing the overall revenue generated from each unit recycled. On the other hand, reducing costs is equally important. This can be achieved by lowering labor costs, optimizing transportation expenses, and minimizing utility costs. Additionally, incentives from governments, subsidies for facility creation, and potentially lower land acquisition costs can also contribute to reducing overall operational costs.

By effectively implementing these strategies—improving technology to increase material recovery rates and reducing operational costs—PV recycling facilities can enhance their revenue streams and improve profitability in the competitive renewable energy market.

V. Conclusion

The growth of PV solar modules is a positive step towards a sustainable future, but it also brings about concerns related to the proper disposal and recycling of PV waste. The increasing amount of PV waste can have significant environmental impacts if not dealt with properly. The UK has implemented a regulatory framework to control waste and ensure environmental protection, but other developing countries lack such regulations, which can have long-term impacts on human health and the environment. The current recycling approaches for PV modules rely on down cycling, which only recovers a portion of the value and materials. Thus, there is a need for innovative and strategic recycling approaches that can recover more materials and value from PV waste.

Recycling PV waste is critical to resource conservation, reduced environmental effects, development of a circular economy, and safe disposal of PV modules and components. There are various methods for recycling PV waste, including physical, chemical, and thermal separation. However, the efficiency of these technologies depends on the type of PV waste, purity of the recovered components, and environmental impact of the recycling process. It is essential to recycle PV waste in an ecologically appropriate way to contribute to a sustainable energy future.

The paper has mainly emphasized on evaluating the current PV waste recycling process in the UK and address the necessity of recycling the PV waste in an effective way that will increase the efficiency of the whole recycling process. This research has selected Cornwall in the UK to measure the efficiency rate of the different recycling process of PV modules. From the analysis, it was calculated that the total operational expenses of the plant in a year was £5,760,310.66. From the calculation of revenue obtained by the market value of recovered materials, it was observed that the recycling facility could generate total yearly revenue of £5,852,745.80 approximately. It can be concluded from the analysis that the plant will generate a profit of £92,435.14. This gives an ROI of approximately 2%. The profits can fluctuate at the end of the year as it depends on the variable expenses on transport and fluctuations in the prices of recovered metals.

In addition to its relevance to the UK context, the model presents a versatile framework applicable to various other countries grappling with photovoltaic (PV) recycling challenges. Its strength lies in its adaptability to incorporate regional factors such as utility costs, labor rates, land availability, transportation logistics, and governmental incentives. By adjusting these parameters to suit specific local conditions, stakeholders in different nations can effectively utilize the model to evaluate the feasibility and optimize the economics of PV recycling initiatives. The qualitative insights and strategic recommendations generated from this study are transferable, offering valuable guidance to policymakers, industry leaders, and researchers worldwide. Therefore, the model not only enhances understanding of PV recycling dynamics in the UK but also serves as a valuable tool for advancing sustainable practices in PV waste management globally.

The market for the reuse and repairing of PV panels is high due to the growing demand for them. In a study conducted by Klugmann-Radziemska and Kuczyńska-Łażewska [49], the researchers examined the environmental implications of utilizing recycled silicon wafers in solar cell manufacturing compared to manufacturing cells without recycled silicon. Their findings indicated that recycling silicon wafers leads to significant reductions in raw material consumption, production costs, and greenhouse gas emissions by 42%. Similarly, Artaş *et al.* [50] performed a comparative assessment of carbon dioxide emissions and economic expenses associated with solar modules made from recycled materials versus those produced without recycling. They concluded that recycling waste PV modules not only reduces environmental pollution but also promotes the reuse of rare materials, thereby generating economic benefits.

The future market for recycling is expected to rise, and proper planning will allow for channelizing economic benefits. However, dismantling smaller PV units depends on the type and location, and skilled workers are required to avoid any damage to PV panels.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Conceptualization, D.G.P., F.M.-S. and S.H.A.-B.; methodology, D.G.P., and F.M.-S.; formal analysis, D.G.P., and F.M.-S.; investigation, D.G.P.; resources, F.M.-S.; data curation, D.G.P.; writing—original draft preparation, D.G.P. and F.M.-S.; writing—review and editing, D.G.P., F.M.-S. S.H.A.-B., A.A.M. and M.K.A.K.; visualization, D.G.P., and F.M.-S.; supervision, F.M.-S.; project administration, F.M.-S.; funding acquisition, F.M.-S. All authors have read and agreed to the published version of the manuscript. All authors had approved the final version.

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