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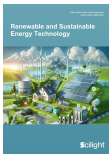

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Article

Comprehensive Design of Solar Photovoltaic Circular Economy for Non-PV-Manufacturing Nations

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Abstract: By 2050, globally accumulating waste from end-of-life solar photovoltaic (PV) panels will surpass 78 million tonnes as the global annual installations are exceeding predictions. PV dismantling and circular economy approaches are evidently appealing to countries that are leading PV manufacturing industries. Therefore, they confidently built PV waste management centers (PVWMCs). But what about the non-PV-manufacturing nations with large PV installations? This work presents a stable proactive long-term (2030–2075) solution through designing internal technical specifications and supply chain management of PVWMCs for two PV technologies. The proposed designs collect PV wastes then effectively store or dismantle them to output byproducts that can be stored or shared with non-PV industries; industrial symbiosis (IS). A Mixed-Integer Nonlinear Programming (MINLP) optimization model was created to balance multiple tradeoffs after projecting annual PV wastes. Results demonstrated the PVWMCs' short- and long-term techno-economic profitability, controlled dismantling capacity, and linearized/stabilized materials' supply, which was not achieved before.

Keywords: solar PV; crystalline silicon (c-Si); cadmium telluride (CdTe); mixed-integer nonlinear programming (MINLP); industrial symbiosis; green supply chain management

1. Introduction

Renewable systems are not completely sustainable in balancing between operational awareness [1–3], environmental impacts [4–7], economic feasibility [8–10], and social acceptance [11–14]. Solar PVs are being globally installed in larger numbers and are seen as a very promising technology for future investments, research, and development due to its competitiveness and overall sustainable potential for improvement [15–19]. In order to foster sustainable practices within the photovoltaic (PV) sector, it is imperative to address multifaceted concerns ranging from environmental impact during both construction and decommissioning phases to the operational lifespan of these facilities. Moreover, an in-depth examination of waste management strategies that incorporate economic and social dimensions is warranted. Presently, Power Purchase Agreements (PPAs) governing the majority of PV projects predominantly prioritize economic considerations, particularly the levelized cost of electricity (LCOE), often overlooking social and environmental ramifications [15,20–22]. While efforts are made to mitigate social issues such as noise and pollution during construction and decommissioning, environmental considerations primarily revolve around land-use efficiency and impacts during installation and construction phases, with scant attention to waste management during operational phases. This underscores the exigency for enhanced waste management protocols throughout the entire lifecycle of PV systems, transcending mere end-of-life considerations.

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Circular economy is a comprehensive sustainability development approach that improves the stages of a product's lifecycle from conception to materials' disposal. The best representation of circular economy is through the 10Rs of sustainability [23–28]. These principles are Refurbish [29–33], Remanufacture [34–38], Repurpose [39,40], Recover, Refuse, Rethink, Repair, Reduce, Reuse, and Recycle [23–28]. They work on resource's circularity, multi-level technological development, and holistic sustainable mentality, to hopefully achieve smarter product's manufacturing, operation, lifetime extension, and byproducts innovation. The repurpose principle or IS, shares discarded or used resources within different industries to manufacture products serving different purposes [15,41]. IS has two types: backward and forward. Backward IS receives secondary materials from other industries to manufacture the product. Forward IS; however, supplies the secondary materials of that product to other industries' manufacturing processes. Applying Forward IS for PVs would fit countries with high PV installations, cannot strongly compete in PV manufacturing, and has strong manufacturing capabilities for the PVs' byproducts. Such requirements are fairly met by United Arab Emirates (UAE).

PV waste management plans require collection, dismantling, and byproducts' receiving facilities. Collection facilities require reverse logistics with their corresponding costs. Dismantling facilities require machinery, processing, and regular maintenance costs. Facilities receiving byproducts after dismantling will require forward logistics' corresponding costs. Table 1 summarizes the previous works that tried to design or find the best location for a PV waste management, take back, or dismantling facility. The table compares them in terms of PV technology, country of application, modelling approach, discussion and inclusion of dismantling processes, multi-period continuous projection of PV waste, logistics type, and inclusion of IS concepts. Several modeling approaches were used in the literature like the Mixed-Integer Linear Programming (MILP) [42–46], Linear Programming (LP) [47–50], Greedy Algorithm (GA) [49], and Mixed-Integer Non-Linear Programming (MINLP) [51]. The collected works were carefully selected from a larger review on PVs' waste management and circular economy that went through more than 3000 papers and covered more than 300 papers on various topics, including the optimization and modeling of PV waste management centers [15]. Table 1 shows that none of these works planned wastes management in UAE or any MENA country. Additionally, none of these works covered IS concepts in modeling, designing, or locating of a PV waste management center. The closest and only work that was related to photovoltaics' IS was done by Mathur et al. [52]. They proposed a hypothetical c-Si PVs material life cycle system depending on both backward and forward IS concepts. Their work did not have any mathematical optimization of any sort, but they introduced the PV industry's overall circularity with a good starting point for the researchers to improve. Additionally, their work created some undiscussed research gaps regarding the materials' compatibility between the proposed industries or the PV manufacturing competitiveness of the addressed region or country. Some previous works like the ones done by Mahmoudi et al. [53], and Cucchiella et al. [54], has researched the economic feasibility of some c-Si dismantling facilities, under certain scenarios with some environmental tradeoffs, without mathematical optimizations. Therefore, the current novelties and contributions of this work are: (1) Integration of IS-based approaches in modeling, designing, and locating PVWMCs, (2) Utilization of IS-efficient PV dismantling techniques for c-Si and CdTe technologies, (3) Consideration of reverse-logistics-inspired modeling in evaluating PVWM solutions, opportunities, and challenges, especially while evaluating the impacts of long-term continuous supply of PV wastes on controllability of dismantling capacities and stability of output materials, and (4) PVWM applications and solutions in any Middle East and North Africa (MENA) or any other non-PV-manufacturing nation. Finally, this article is a portion of a bigger effort that aims to enhance PV waste management and projection using models that incorporate influential stakeholders' decision-making aspects, presented in [11].

Table 1. Comparison between this work and previous works in the literature of PV waste management center's locating and designing.

#	Work	PV Tech.	Country	Modelling Approach	Dismantling Processes	Continuous Waste Projection	Logistics Type		IS
							Reverse	Forward	
1	[47]	c-Si	Germany	MILP & LP	✓		✓		
2	[48]	CdTe	Germany	LP	✓				
3	[49]	c-Si	USA	LP & GA			✓		
4	[51]	c-Si, a-Si, CdTe, & CIGS	Germany	MINLP			✓		
5	[42]	-	Australia	MILP			✓		
6	[55]	-	Germany	LP			✓		
7	[43]	c-Si	China	MILP			✓		
8	[44]	c-Si	USA	MILP			✓		
9	[45]	GIS	Australia	MILP			✓		
10	[50]	c-Si, a-Si, CdTe, & CIGS	Australia	LP	✓	✓	✓		
11	[46]	Thin films	Iran	MILP			✓		
12	This work	c-Si & CdTe	UAE	MINLP	✓	✓	✓	✓	✓

2. Technological Designs of the PVWMCs

The proposed PVWMCs' design is examined to prove sustainability competitiveness through eight (2^3) comparative levels that are independently categorized under two PV technologies, two optimization goals, and two PV waste projection scenarios, regardless of the targeted nation or economies. The PV technologies are Crystalline Silicon (c-Si) and Cadmium Telluride (CdTe). The main goals are to optimize the Supply Chain Networking of Management (Figure 1a) and to optimize the internal technical specifications (c-Si in Figure 1b and CdTe in Figure 1c). The received PV waste and each of the output byproducts has a separate inventory to be managed throughout the lifespan from 2030 to 2075. The scenarios are the regularly lost, or decently maintained, and the early lost, or poorly maintained, PVs' waste projection scenarios.

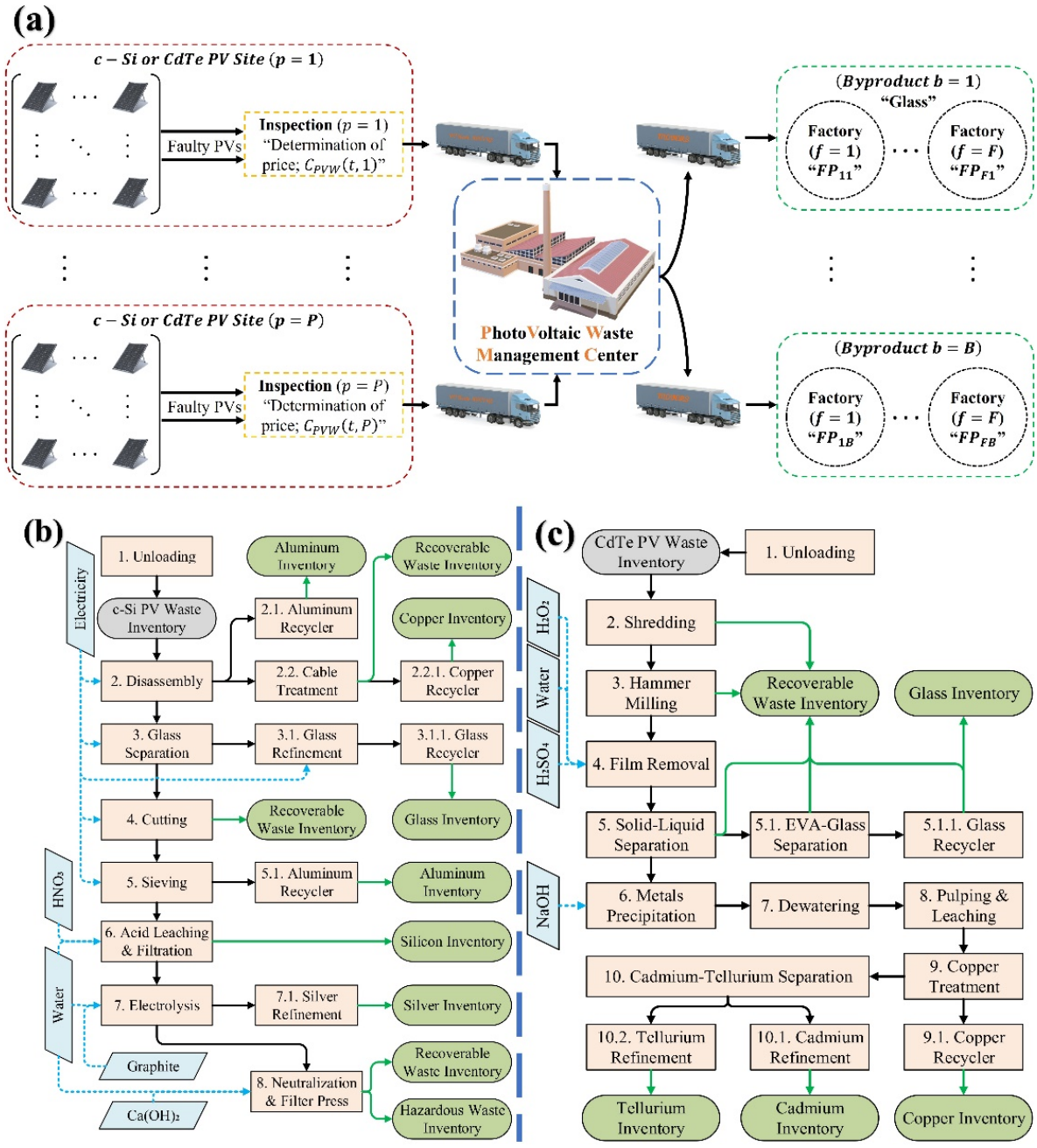

Figure 1. External and Internal designs of the PVWMCs. (**a**), External management, and configurations of the PVWMCs' supply chain through reverse logistics (left side of **a**) to collect or buy PV wastes after technical quality inspection to determine their price. Forward logistics (right side of **a**) with IS to sell each category of output byproducts or secondary materials to a non-PV-manufacturing facility among competing candidates for the best price per category. (**b**), Internal design of the c-Si PVWMC. (**c**), Internal design of the CdTe PVWMC.

2.1. Internal Design of the c-Si PVWMC

Figure 1b shows a diagram of the internal dismantling processes for the c-Si photovoltaic technology, adjusting on the processes proposed by previous works [56,57]. The blue color represents the required materials and electricity, the green color represents the final byproducts as green outputs of a sustainable (green) process, and the rest of the colors represent the neutrality and initiative of the processes in creating dangerous wastes to useful byproducts. The incoming PV waste is transported to the PVWMC location then unloaded using a forklift and moved to their inventory. The disassembly process mechanically separates major parts like the aluminum frame, junction box, and glass with the Ethylene Vinyl Acetate (EVA) layer. Followed by a special process (glass separation) to detach the glass from the PV cell and the polymers. Then comes the size reduction and EVA extraction within the cutting phase. The sieving phase represents the final accumulation of internal aluminum. The acid leaching and filtration phase are a series of chemical processes to recover secondary market Silicon. Silver is separated on graphite rods through electrolysis. Neutralization and filter press phases will finalize the whole process through extracting the last hazardous wastes and recoverable wastes.

2.2. Internal Design of the CdTe PVWMC

Figure 1c shows a diagram of internal dismantling processes for CdTe photovoltaic technologies, adjusting on the processes proposed by First Solar [58–61], and other researchers [48,62,63], depending on their cumulative results. Unloading is when the incoming PV waste is transported to the PVWMC location then unloaded using a forklift and moved to their inventory. CdTe PV Waste Inventory is an inventory with a defined capacity and CdTe-specific compatibility. Shredding is the removal of frames, if existed, and the PV modules are cut into two pieces. Hammer Milling is when the two large pieces are crushed into small pieces (4–5 mm). Film Removal is when most of the ethylene vinyl acetate (EVA) film is removed under strict dust control and highly efficient particulate air filters. Solid-Liquid Separation is when the fragments are put into a reactor column where a strong acid is used to separate the EVA and glass fragments from the metallic acid solutions. EVA-Glass Separation is when a vibrating screen is used to recover glass pieces from the remaining EVA. Glass Recycler means that the glass pieces are rinsed and cleaned to be ready for secondary market. Metals Precipitation is when the sodium hydroxide (NaOH) is added to increase the pH to 10 and start the metal separation process with precipitation of Cadmium and Telluride. The next process is dewatering the precipitated metals to get unrefined semiconductors and other metals. Pulping and Leaching means separation, treatment, liquification, and removal of contaminants. Copper Treatment is a wet process that extracts and separately deals with copper fragments and sends it to the copper recyclers to get secondary market copper. Finally, Cadmium-Tellurium Separation is receiving the CdTe filter cakes to separate and refine cadmium and telluride chemicals through precipitation and reduction.

3. Development of the MINLP Optimization Model

The model assures the economic profitability of the PVWMCs through maximizing the minimum annual profit throughout the whole planning horizon, with considerations for the time value of money, inflation, and other specifications. The revenues come from sold byproducts, while the costs are mainly represented by reverse logistics costs from the PV projects' sites to the PVWMC, cost of input PV waste, internal processing or operation and maintenance (O&M) costs, and forward logistics costs from the PVWMCs to chosen factories. Forward and reverse logistics costs are combinations of transportation, handling services, and overall management costs. Due to UAE's geography, transportation is limited to trucks, and they account for annual fuel cost, chosen trucks' average fuel consumption, and trucks' allowable load, but similar analysis can be done for any type of transportation. Table 2 shows the indices, scalars, parameters, auxiliary variables, and decision variables used in the proposed model.

Table 2. The model's indices, parameters, and variables.

Notation	Description
Indices and Sets	
$t \in \mathcal{T} = \{\tau, \tau+1, \dots, LY\}$	Annual time periods are indexed by t, where τ is the starting year of the PVWMC's operation, LY is the last year in the planning horizon, and T = $\lvert\mathcal{T}\rvert$ is the number of planning years.
$p \in \mathcal{P} = \{1, \dots, P\}$	PV sites or projects indexed by p, where P = $\lvert\mathcal{P}\rvert$ is the total number of PV sites.
$b \in \mathcal{B} = \{1, \dots, B\}$	Byproducts are indexed by b, where B = $\lvert\mathcal{B}\rvert$ is the total number of byproducts.
$f \in \mathcal{F}(b) \subset \mathcal{F}$	Factories are indexed by f that can buy byproduct b, where $\boldsymbol{\mathcal{F}}$ is the set of all candidate factories, $\mathcal{F}(b)$ is the subset of factories eligible for byproduct b, and F = $\lvert\mathcal{F}\rvert$ is the total number of factories.

Table 2. *Cont.*

Notation	Description
Scalars	
S	Scenario-specific shape factor/parameter for Weibull Distribution.
ALT	Average lifespan/lifetime, in years, for each PV technology.
PY	Planning and designing (present) year.
CC_{Lat}	Conversion constant, from latitude degrees to km, $CC_{Lat} = 110.574 \frac{\text{km}}{^{\circ}\text{N}}$.
CC_{Long}	Conversion constant, from longitude degrees to km, $CC_{Long} = 111.320 \frac{\text{km}}{^{\circ}\text{E}}$.
Parameters	
OY_p	Starting year of operation, for PV site *p*.
TPC_p	Total Power Capacity, in Watts (W), generated in site *p*.
MM_p	Unitary Mass of PV modules, in tonnes, operational in site *p*.
MRP_p	Unitary Rated Power of PV modules, in *W*, operational in site *p*.
$i(t)$	Inflation-corrected interest rate, during year *t*.
$C_{fuel}(t)$	Fuel cost, for one litre of fuel, during year *t*.
$C_{service}(t,p)$	Logistics' service cost, per tonnes of waste, from project site p, during year *t*. This also aggregates environmental legislations, taxations, or trading accompanying transportation and logistics, depending on the transportation technology.
$C_{transport}(t)$	Unitary transportation cost, per tonnes of PV waste, per km, during year *t*.
$TFC(t)$	Average Truck's Fuel consumption, in litres of fuel per km, during year *t*.
$TAL(t)$	Truck's Average Load, in tonnes, during year *t*.
W_p^t	PV Waste mass coming from site *p*, in tonnes, during year *t*.
TW^t	Total mass, in tonnes, of PV Waste coming from all the sites during year *t*.
Lat_p	Latitude coordinate, in degrees, for PV project site *p*.
$Long_p$	Longitude coordinate, in degrees, for PV project site *p*.
Lat_{fb}	Latitude coordinate, in degrees, for factory *f*, receiving byproduct *b*.
$Long_{fb}$	Longitude coordinate, in degrees, for factory *f*, receiving byproduct *b*.
ω_b	PVs' original mass percentage of byproduct *b*.
η_b	PV wastes' mass recovery rate of byproduct b.
FP_{fb}	Price suggested by factory *f*, for byproduct *b*.
$C_{PVW}(t,p)$	Cost of PV waste, per tonnes, from site *p*, to be processed during year *t*.
$C_{O\&M}(t)$	Operations and Maintenance cost, per tonnes of input PV waste, during year *t*. This aggregates costs of energy, water, and materials needed, color-coded in blue in Figure 1b,c, as well as any corresponding environmental taxation due to internal processing. This also aggregates any regular handling of secondary pollution causes.
MNF_b	Target number of factories chosen to buy byproduct *b*, $(MNF_b \leq \lvert\mathcal{F}(\text{b})\rvert, \ \forall b \in \mathcal{B})$.
Auxiliary Variables	
Z	Minimum value among all present values of annual profits.
$PP(t)$	Present value of profit at year *t*.
$AP(t)$	Profit at year *t*.
D_p	Distance, in km, from project site *p*, to the PVWMC.
D_{fb}	Distance, in km, from the PVWMC, to factory f that is buying byproduct *b*.
$WInv^t$	PV Waste Inventory capacity, during year *t*, in tonnes.
PO_b^t	Processing output of byproduct *b*, during year *t*, in tonnes.
Inv_b^t	Inventory capacity for byproduct *b*, during year *t*, in tonnes.
TPP	Total present value of profit.
$CapC$	Capital Cost of the processing machine and building cost of the PVWMC.
Decision Variables	
Y	Latitude coordinate, in degrees, for the PVWMC.
X	Longitude coordinate, in degrees, for the PVWMC.
PI^t	Processing Input, in tonnes, within the PVWMC, during year *t*.
S_{fb}^t	Mass of byproduct *b*, in tonnes, sold to factory *f*, during year *t*.
L_{fb}	1 if byproduct *b* is chosen to be sold to factory *f*, 0 otherwise.

3.1. Objective Function and Constraints

Equation (1) picks the minimum present profit using Equation (2), instead of the whole summation, to distribute the processing inputs and outputs over the whole planning horizon. Such an approach improves possible utilizations of every inventory and gives the best economic annual dismantling capacity for the PVWMCs. Equation (3) accounts for different parts of revenues and costs. The initial component in Equation (3) delineates the selling prices and the logistics costs to be delt with between the PVWMCs and the chosen factories to buy each byproduct. The second term of Equation (3) corresponds to the reverse logistics to be delt with between the PV project sites and the PVWMCs. The third component of Equation (3) delineates the expenses associated with input PV waste as well as the services and management part of the reverse logistics costs. The fourth term of Equation (3) corresponds to the internal processing/O&M costs. Equation (4) calculates the unitary transportation cost per tonnes of PV waste. Equations (5) and (6) are the expressions for the arc distance between two points. Equation (7) [11,64], incorporates the latest photovoltaic probability loss methodology as outlined in a comprehensive report jointly authored by the International Renewable Energy Agency (IRENA) and the International Energy Agency Photovoltaic Power Systems Programme (IEA-PVPS) [16]. This methodology, rooted in the Weibull distribution [65], delineates two primary scenarios: regular-loss and early-loss, each characterized by distinct shape parameters (S), extensively employed in PV loss estimation studies [66–69]. The application of the Weibull distribution in assessing annual power loss has been extensively investigated. Under the presumption that power loss probability equates to module loss probability when total power loss over a defined period stems from an integer number of modules, this assumption holds particular relevance for long-term planning horizons, as is pertinent to this study. This also means that long-term planning of multiple large PV projects can allow for a strong assumption that equates the probability of power loss to the probability of mass loss. Equation (7) serves as a comprehensive model enabling the direct computation of annual total PV waste mass for individual PV projects, aggregating these estimates across all projects. It facilitates the calculation of annual total PV waste mass per project by multiplying the unitary mass of PV modules by their numbers derived from rated power ratios in each PV project. Equations (8) and (9) restrict the PV waste's inventory and assure the non-negativity of the processing input as well as the inventory itself. Equation (10) makes sure that the PVWMC dismantles all the input PV waste by the end of the planning horizon, which provides an innovative and controllable green supply chain management solution. Equation (11) represents the annual processing output as a function of the processing efficiency and the mass percentage of each byproduct. Equations (12) and (13) restrict the annual output inventory for each byproduct and ensure their non-negativity. Equation (14) makes sure that all the output byproducts are fully sold by the end of the planning horizon. Equation (15) assures that the sold amounts are only assigned to the chosen factories. It is a linearization of the conditional assertion stating: "if $L_{fb} = 0$ then $\sum_{t\in\mathcal{T}} S_{fb}^{t} \leq 0$", and the big value concept is replaced with the term "$\sum_{t\in\mathcal{T}} PO_{b}^{t}$" which can also be represented by "$\sum_{t\in\mathcal{T}} TW^{t}$" or any other big value that will lower the computational load while not impacting the upper limit of "$\sum_{t\in\mathcal{T}} S_{fb}^{t}$". Equation (16) restricts the number of chosen factories for each byproduct. Equation (17) is the non-negativity constraint for every sold amount of each byproduct. Equation (18) is the binary condition that supports Equations (15) and (16).

$$Maximize\ Z = Min\big(PP(\tau), PP(\tau+1), \ldots, PP(LY)\big) \tag{1}$$

$$PP(t) = \frac{AP(t)}{\big(1+i(t)\big)^{t-PY}}, \qquad \forall t \in \mathcal{T} \tag{2}$$

$$\begin{aligned} AP(t) = {} & \sum_{b\in\mathcal{B}} \sum_{f\in\mathcal{F}(b)} \big(FP_{fb} - C_{transport}(t) D_{fb}\big) S_{fb}^{t} - \sum_{p\in\mathcal{P}} C_{transport}(t)\, W_{p}^{t}\, D_{p} \\ & - \sum_{p\in\mathcal{P}} \big(C_{PVW}(t,p) + C_{service}(t,p)\big) W_{p}^{t} - C_{O\&M}(t) PI^{t}, \qquad \forall t \in \mathcal{T} \end{aligned} \tag{3}$$

$$C_{transport}(t) = C_{fuel}(t)\left(\frac{TFC(t)}{TAL(t)}\right), \qquad \forall t \in \mathcal{T} \tag{4}$$

$$D_{p} = \sqrt{\big[\big(X - Long_{p}\big)\, CC_{Long}\, cos\big(Y - Lat_{p}\big)\big]^{2} + \big[\big(Y - Lat_{p}\big)\, CC_{Lat}\big]^{2}}, \qquad \forall p \in \mathcal{P} \tag{5}$$

$$D_{fb} = \sqrt{\big[\big(X - Long_{fb}\big) CC_{Long}\, cos\big(Y - Lat_{fb}\big)\big]^{2} + \big[\big(Y - Lat_{fb}\big)\, CC_{Lat}\big]^{2}}, \qquad \forall f \in \mathcal{F}(b), \forall b \in \mathcal{B} \tag{6}$$

Subject to:

$$TW^t = \sum_{p\in\mathcal{P}} (MM_p)\left(\frac{TPC_p}{MRP_p}\right)\left(\frac{S}{ALT}\right)\left(\frac{t-OY_p}{ALT}\right)^{S-1} e^{-\left(\frac{t-OY_p}{ALT}\right)^S}, \qquad \forall t \in \mathcal{T} \tag{7}$$

$$WInv^t = TW^t + WInv^{t-1} - PI^t, \qquad \forall t \in \mathcal{T} \tag{8}$$

$$WInv^t \geq 0, \qquad \forall t \in \mathcal{T} \tag{9}$$

$$WInv^{LY} = 0 \tag{10}$$

$$PO_b^t = PI^t \omega_b \eta_b, \qquad \forall t \in \mathcal{T}, \forall b \in \mathcal{B} \tag{11}$$

$$Inv_b^t = PO_b^t + Inv_b^{t-1} - \sum_{f\in\mathcal{F}(b)} S_{fb}^t, \qquad \forall t \in \mathcal{T}, \forall b \in \mathcal{B} \tag{12}$$

$$Inv_b^t \geq 0, \qquad \forall t \in \mathcal{T}, \forall b \in \mathcal{B} \tag{13}$$

$$\sum_{b\in\mathcal{B}} Inv_b^{LY} = 0 \tag{14}$$

$$\sum_{t\in\mathcal{T}} S_{fb}^t \leq L_{fb} \sum_{t\in\mathcal{T}} PO_b^t, \qquad \forall b \in \mathcal{B}, \forall f \in \mathcal{F}(b) \tag{15}$$

$$\sum_{f\in F(b)} L_{fb} = MNF_b, \qquad \forall b \in \mathcal{B} \tag{16}$$

$$S_{fb}^t \geq 0, \qquad \forall t \in \mathcal{T}, \forall b \in \mathcal{B}, \forall f \in \mathcal{F}(b) \tag{17}$$

$$L_{fb} \in [1,0], \qquad \forall b \in \mathcal{B}, \forall f \in \mathcal{F}(b) \tag{18}$$

3.2. Post-Optimality Computations of Capital Costs and Profit

The annual PVWMCs' dismantling capacity, in tonnes of technology-specific-PV wastes, shown in Equation (19), must be expressed as a function of the maximum processing input. The volume of the PV waste inventory can be calculated through the average dimensions of the PV modules and the weekly average value of the maximum annual inventory. A similar approach can be applied to every byproduct's inventory, using their density. The capital cost accounts for the construction, inventory, and equipment costs. An approximation of the capital cost, as a function of the annual dismantling capacity, is shown in Equation (20), which was curve-fitted using data from several research papers and internationally built PV dismantling facilities for c-Si and CdTe PV technologies [42,44,47,53,55,70]. The equation is reliable for facilities with an annual dismantling capacity of over 476.272 tonnes of PV waste. Finally, the present value of the total profit over the whole planning horizon, with the consideration of capital cost, can be expressed as shown in Equation (21).

$$Annual\ Dismantling\ Capacity(Tonnes) = Max(PI^{\tau}, PI^{\tau+1}, \ldots, PI^{LY}) \tag{19}$$

$$CapC = \$4241 \times \left(Annual\ Dismantling\ Capacity(Tonnes)\right)^{0.6} \tag{20}$$

$$TPP = \sum_{t\in\mathcal{T}} PP(t) - \frac{CapC}{\left(1+i(\tau)\right)^{\tau-PY}} \tag{21}$$

3.3. Non-Linearity Solving Method

Other than the instantly noticed non-linearity in Equations (5) and (6), Equation (3) is also non-linear. This non-linearity in Equation (3) can be seen in the first term of the equation, due to the multiplication between the internal variable D_{fb} and the iterative variable S_{fb}^t. For simplicity, better visualization, and better understanding of the model's non-linear relationships, the two optimization goals can be solved in separate models if there was no price competition between all the factories that are willing to buy the same byproduct. This is generally

acceptable since the PVWMCs' management will be the ones to decide the prices under such assumption, without the need for the unrealistic operational competition. The prices' unity among factories of the same byproduct makes it easy to separate logistics costs, individual profits, reverse logistics, and internal processing costs. Therefore, Equation (3) will need a supporting equation that is similar to Equation (3) but only considers the transportation costs as a function of material percentages, instead of material mass, which will help in ignoring the annuity factor. The first function will still use Equations (5) and (6), which can be solved using several methods, like the Generalized Reduced Gradient Non-linear solving method. The supporting equation will solve for the best centralized (single facility) PVWMC's longitude and latitude coordinates, taking into consideration the locations of all the PV projects across the country and all the participating factories for each byproduct. It will calculate the arc distances D_{fb} and D_p, which then be substituted in Equation (3), as constant parameters, converting the model from a non-linear model to a mixed integer model. The model then will use a linear objective function but has binary variables in addition to Equation (2) being non-linear. Though, the model as a whole can still be solved using the Generalized Reduced Gradient Non-linear solving method. A decentralized (multiple-facility location) model will have all the distances accurately pre-defined, which will release the model from the need of the supporting equation. Equation (7) is also nonlinear, but it is not a direct part in solving the model, as it is simply used to substitute parameters and scalars in a function over indices to calculate the input data for the actual model. The model delineated in this study is articulated in a technically coherent manner, facilitating its implementation across various solving software platforms, with particular applicability to the General Algebraic Modeling System (GAMS) software (any version). This is a mathematical modeling and optimization approach following well-known and well-established practices in the operations research field of study, where not only mathematical derivations are indirectly utilized but also dire needs for optimization are satisfied through balancing multiple tradeoffs presented in the current problem solved in this model.

4. PVWMCs' Implementation in UAE

4.1. Data Selection and Collection

A meticulous data collection and reliability assessment protocol was executed for all accessible large-scale PV installations in the UAE. Table 3 presents the compiled specifications obtained from all sizable c-Si and CdTe PV installations situated within the UAE. The data was meticulously curated and cross-referenced from various online sources including the websites of PV project owners [71–77], project operators [77–80], and PV module suppliers [81–87]. Typically, these projects are jointly owned by two entities: the primary investor and the facilitator, who may have tendered the project and contracted the operator. In instances of conflicting or discrepant data provided by different stakeholders, precedence was given to the most comprehensive data set, typically sourced from the operator's website. Additionally, where available, supplementary data and general information were gleaned from PPAs. Although numerous PV projects are operational across diverse regions of the country, some are privately owned, with their specifications not publicly disclosed online. Therefore, these privately owned PV projects were excluded from the analysis, to maintain the reliability and consistency of the selected data. Table 4 shows the collected latitudal and longitudal coordinates of the best factories for each of the byproducts. Due to their relevant industrial experience, the authors are familiar with the regulations and PPAs of the UAE's PV-related projects, which allowed the collection of such detailed, accurate, and guaranteed data. Therefore, UAE was the only focus for data related to PV projects. Owing to the disproportionate installations' distribution of PVs throughout UAE, the model would prefer locating the facility closer to some PV projects, to reduce the reverse logistics and transportation costs. Since the facility receives 100% of the PV waste and delivers a partial percentage to the non-PV industries, then the location would not be shifted too far away from most byproducts. Such logical understanding with its supporting constraints and data guarantees that the model will locate the facility within the mesh created by all the PV projects and factories. This UAE-based mesh disregards any factories that are far away from it, like international or MENA-scale factories outside the UAE, unless they provide unrealistic competition in comparison with the UAE-based factories to overcome the high forward logistics and transportation costs. Therefore, addition of such data would tire the model and lower its solving speed which might lower the accuracy of the results obtained due to the non-linear nature of some equations. Table 5 lists all the recoverable materials in commercial c-Si and CdTe PV modules, regarding their recovery percentage, and secondary market prices. The term "Other wastes" in Table 4 refers to all the byproducts that are included in the processes' outputs in Table 5 but are not specified in Table 4 for not having dedicated manufacturing facilities in UAE. Table 6 lists the operation and maintenance (O&M) costs, logistics specifications, and the inflation rate. The logistics services include the handling services of the inventories' flow, drivers' costs, and administrative or managerial services related to the overall PVWMC's logistics and supply chain. The operation and maintenance costs include materials, labor,

electricity, and maintenance costs. The electricity cost, especially, was adjusted to UAE, considering worst case scenario (maximum industrial consumption rates). All the costs were adjusted to include the only tax rate applied in UAE, which is the Value Added Tax (VAT), applied on most types of goods and services in the country. Most of the values in Tables 5 and 6 were properly weight averaged from previous researches [42,44,47,48,53,55,62,63,70], websites [88,89], or were assumed by the authors, like the inflation rate.

Table 3. Details of all large-scale CdTe and c-Si PV sites in UAE. Adapted from [11].

PV Project Name		Masdar City		Mohammed Bin Rashid Al Maktoum Solar Park							Noor Abu Dhabi	Camelicious
				Phase I	Shuaa Energy I	Shuaa Energy II			Noor Energy I	Shuaa Energy III		
						Stage I	Stage II	Stage III	Stage III			
	PV Technology	c-Si	CdTe	CdTe	CdTe	CdTe	c-Si	c-Si	CdTe	c-Si	c-Si	c-Si
TPC_p:	Total Power Capacity (10^6 W)	5	5	13	260	200	300	300	250	930	1200	3.6816
MM_p:	Modules' Mass (tonnes)	0.03	0.01	0.012	0.012	0.01	0.03	0.03	0.034	0.03	0.02	0.0231
MRM_p:	Module's Rated Power (W)	275	72.5	85	112.5	123	550	550	470	550	375	400
OY_p:	Operation's Starting Year	2009	2009	2014	2017	2018	2019	2020	2021	2023	2019	2021
	PPA duration (Years)	25	25	25	25	25	25	25	25	25	25	25

Table 4. Location coordinates for UAE PV sites and best UAE-available factories for each byproduct.

Type	Facility Name	Lat_p and Lat_{fb} Latitude (°N)	$Long_p$ and $Long_{fb}$ Longitude (°E)
Large-scale PV Site	Masdar City	24.4346646856961	54.6088060117035
	Mohammed Bin Rashid Al Maktoum Solar Park	24.7808131893177	55.3659395505799
	Noor Abu Dhabi	24.5407522670930	55.4401625699714
	Camelicious	25.0323478359373	55.4190356273222
Glass	f_{11}	25.1786008169525	55.3390508765420
	f_{12}	25.1151614247813	55.2250406722300
	f_{13}	25.3189217968150	55.4440590514327
Aluminium	f_{21}	25.3924703755935	55.4914743719522
	f_{22}	25.2811877628420	55.3879064864642
	f_{23}	25.3204414642726	55.4366772735835
Silicon	f_{31}	25.2881664570349	55.4419960453560
	f_{32}	25.2857113856972	55.4369710838542
Copper	f_{41}	25.2899560646688	55.3891429651894
	f_{42}	24.3289425220215	54.4729619878108
	f_{43}	24.9645607535724	55.0245729653365
Other Wastes	f_{51}	25.2944625614413	55.6494911678772

Table 5. Materials' recovery percentages and secondary market prices.

Byproduct (b)	Recovery Percentages ($\omega_b \eta_b$)		FP_{fb} Secondary Market Price ($/tonnes)
	c-Si	CdTe	
Glass	61.7000%	85.7147%	441.87
Aluminium (Al)	17.5625%	0.0481% *	2226.24
Silicon (Si)	6.2700%	0.3000% *	3512.65
Copper (Cu)	0.7467%	0.6594%	7147.28
Cadmium (Cd)	-	0.1140%	1099.92
Telluride (Te)	-	0.1140%	89,002.32
Silver (Ag)	0.0760%	-	646,550.06
Lead (Pb)	0.0005% *	0.0005% *	2050.09
Tin (Sn)	0.0211% *	-	15,899.92
Useful Waste	7.2720%	3.5000%	272.26
Hazardous/Contaminated Waste	6.3512%	9.5493%	0.00

*: Needs extra processing if it will be sold separately to specialized factories.

Table 6. Logistics specification, other costs, and inflation rate.

Parameter	Unit	Value
Trucks' Average Fuel Consumption	(litre/km/truck)	0.326
Trucks' Average allowable Load	(tonnes/truck)	4.536
Fuel cost	($/litre)	0.85
Unitary Logistics service cost	($/tonnes)	123.06
Price of incoming c-Si PV waste/modules	($/tonnes)	330.95
Price of incoming CdTe PV waste/modules	($/tonnes)	242.50
O&M Costs for c-Si PVWMCs	($/tonnes)	199.55
O&M Costs for CdTe PVWMCs	($/tonnes)	126.21
Inflation Rate	%	2.00

4.2. Results and Discussions

The PVWMCs will operate from 2030 until 2075 (last waste generating year) and regardless of the waste generation's nonlinearity they will control the processing inputs and produce linearized supply of byproducts (Figure 2), as detailed through the profitable design specifications in Table 7. The PVWMCs are best located close to the Mohammed Bin Rashid Al Maktoum Solar Park, due to the relatively large weight of PVs that are installed in there when compared to other PV projects across the UAE. The reason behind the differences in values, between the regular and early loss scenarios, is that the regular loss scenario would start generating waste later on in the planning horizon. The inventories' weekly sizes are weekly average values of the maximum inventory throughout the whole planning horizon for each material, be it PV waste or any byproduct. The initial flow patterns of inputs and outputs would follow a similar pattern of their respective generated waste, to make sure that all inputs are dismantled, all outputs are sold, and empty inventories as soon as possible. Equations (1), (10), and (14) have proved the logic behind them and successfully achieved their purpose of spreading the processing inputs and sold byproducts throughout the planning horizon, without accumulating them to the year with the maximum present profit. There are no manufacturing facilities in UAE that can benefit from the secondary market Silver, Tin, Lead, Cadmium, or Tellurium. Therefore, they were not included as a dedicated and separate stored output, despite their efficient dismantling potential. Instead, they were added to other byproducts separately stored with recoverable wastes. This is a purely UAE related limitation that only affects the way results are presented but it is completely addressed in the model as shown in Table 5 with each material's composition that was used in the model. The CdTe PV modules have aluminum and silicon within them, but the chosen dismantling processes do not separate them due to development shortage and low material recovery efficiency. Where mentioned, "Others" means the combination of all the other byproducts that were not separately mentioned in the results.

This work highlights important strategies, tools, and concepts that can significantly advance sustainable development research for renewable energies in general and PVs in particular with an application on c-Si and CdTe PVs. The PVWMCs were carefully designed and optimized through economic, technical, and environmental approaches, where the economic approach was the actual assessment and validation tool for the environmental or sustainability development concepts implemented with the assistance of technical dismantling specifications, namely the PV-technology-specific parameters $C_{Processing}(t)$ and $C_{Maintenance}(t)$, as well as the transportation-technology-specific parameters $C_{service}(t,p)$ and $C_{transport}(t)$, aggregating and indirectly representing the environmental and sustainability factors within the economic evaluation in the objective function, specifically the part shown in Equation (3). Deciding the best location of the PVWMC through longitudal and latitudal coordinates allows for flexibility in the construction area. Unfortunately, trying to freely locate and plan for a new centralized center that does not rely on pre-selected locations does not decide the best transportation route from the get-go, but it needs further investigations into the chosen locations. The model assumes that all materials will be sold to local non-PV-manufacturing industries, and existing global-, MENA-, and UAE-awareness driven by cost-saving drives the potential of industrial symbiosis and assures that such assumption is not far from reality [52,90–92]. The IS concepts are extremely interesting in the PV industry and can renew the current methodologies for calculating the PV projects' LCOE after considering the salvage value of every part [64]. Equation (7) considered the accumulated PV waste for every PV project before the PVWMCs' operation-start and assumed that all the PV modules will be reused after the expiration of their main project's PPA, until they are totally disposed of as waste, as suggested by [43,47]. Therefore, the operation-starting year was chosen to be 2030 because the annual waste would then start increasing significantly (Figure 2a). Since the results are over 45 years of continuous dismantling, the duration can be lowered but will stress waste management and condense the workload. The long duration was set to ease the dismantling capacity and lower the size needed for all the inventories and the facility as a whole. Future installations of c-Si and CdTe PV projects will require higher dismantling capacity or longer waiting

duration, so there will always be a tradeoff between capacities and time. Figure 3a,b show the annual profits under all scenarios from c-Si and CdTe PVs, respectively. The figures do not include the capital costs as they require investment and payback plans, which are beyond this work's scope. However, the results show that if the UAE implements the specifications shown in Table 7 then it would pay back the capital costs in less than two years, regardless of technology or scenario, and it would maintain profitability for all years forward.

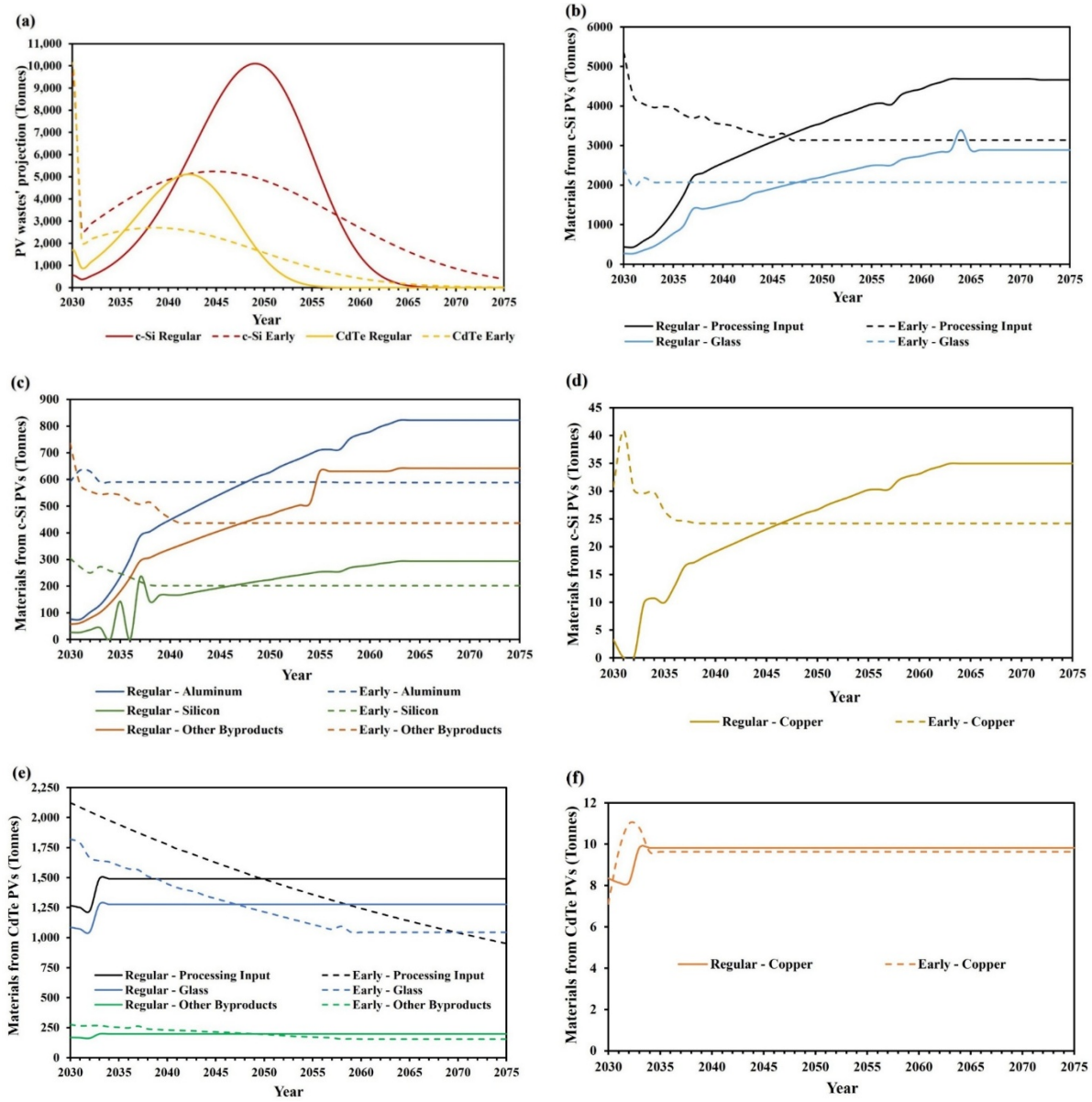

Figure 2. Materials flow in and out of the proposed c-Si and CdTe PVWMCs under scenarios of regular and early loss. (**a**), Annual PV Waste generated from all the large-scale c-Si and CdTe PV projects in UAE. (**b**), c-Si PVWMC's processed input and glass output. (**c**), c-Si PVWMC's output aluminum, silicon, and the other byproducts. (**d**), c-Si PVWMC's output copper. (**e**), CdTe PVWMC's processed input, glass, and the other non-copper outputs. (**f**), CdTe PVWMC's output copper.

Table 7. PVWMC's designs' specifications.

PV Technology	c-Si		CdTe	
PV Waste Projection Scenarios	**Regular**	**Early**	**Regular**	**Early**
Average Annual Profit ($/year)	2,979,000	2,926,000	762,065	754,850
Capital Cost ($)	676,200	733,000	340,060	420,376
PV waste inventory's capacity (tonnes/week)	1436	614	679	369
Dismantling capacities (tonnes/year)	4688	5359	1491	2123

Table 7. *Cont.*

PV Technology		c-Si		CdTe	
PV Waste Projection Scenarios		**Regular**	**Early**	**Regular**	**Early**
Byproducts' inventories' capacities (tonnes/week)	Glass	65.185	45.959	24.573	34.989
	Aluminium	15.809	12.208	-	-
	Silicon	5.644	5.843	-	-
	Copper	0.672	0.786	0.189	0.211
	Others	12.353	14.141	3.806	5.311
Location Coordinates	Latitude (°N)	24.7818337201970			
	Longitude (°E)	55.3661551487313			
Unitary Byproducts' forward logistics costs ($/tonnes)—the chosen byproduct-specific manufacturing facility	Glass	2.435 (f_{12})			
	Aluminium	3.389 (f_{22})			
	Silicon	3.443 (f_{32})			
	Copper	2.593 (f_{43})			
	Others	3.859 (f_{51})			

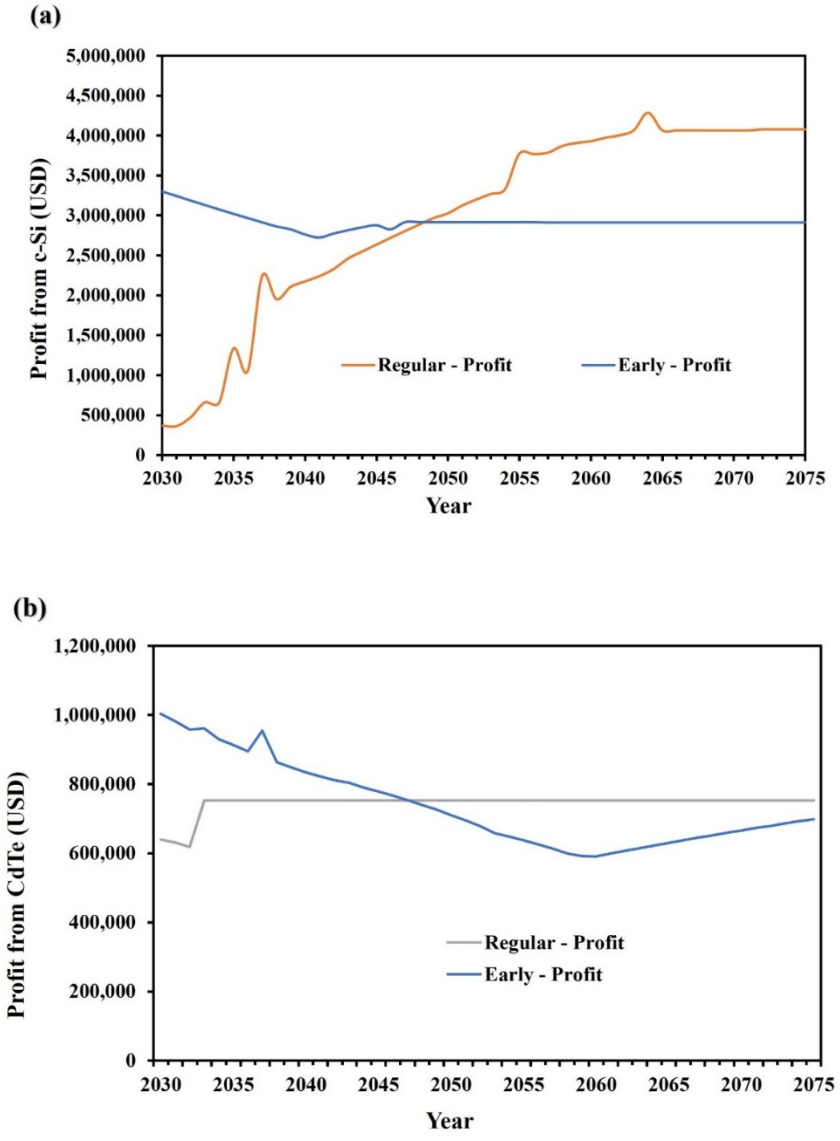

Figure 3. (**a**), Annual profit generated from c-Si PV under both regular and earlly scenarios. (**b**), Annual profit generated from CdTe PV under both regular and earlly scenarios.

5. Conclusions and Recommendations

The model is as concisely comprehensive as possible for the scope of this paper, and it is flexibly usable for any green supply chain management, optimization, and resilience application for any country or nation, not just

UAE. This is a mathematical modeling and optimization approach following well-known and well-established practices in the operations research field of study, where not only mathematical derivations are indirectly utilized but also dire needs for optimization are satisfied through balancing multiple tradeoffs presented in the current problem solved in this model. Tradeoffs such as (1) choosing between increasing the decommissioning capacity of the PVWMCs' facilities to account for the maximum PV waste generation throughout the planning horizon, or decreasing it to reduce the capital costs, avoid building a facility that will utilize its maximum capacity only during maximum PV waste generation periods, and preferably store the incoming waste and manage it over multiple periods, (2) choosing between positioning the PVWMCs closer to the sources of PV waste generated (i.e., PV projects) or closer to the source of revenue (i.e., non-PV-manufacturing industries), taking into consideration that there are multiple PV projects with different locations and different annual generation of waste, and there are multiple non-PV manufacturing industries with different locations and different preferrable price per material. The model selected the best supply chain network configurations, location, and internal specifications for a long-lasting, sustainable, and profitable PVWMC for c-Si technologies. The data showed that the total PV waste that will generate from all the c-Si PV projects in UAE accumulates to 158,000 tonnes. The model generated results from 2030, as the PVWMC's operation-starting year, until 2075, as the last year to ever generate waste from any project. However, the model showed that the annual dismantling capacities of the PVWMC were 4700 and 5400 tonnes under the regular and loss scenarios, respectively. The average annual profits were $2,979,000 and $2,926,000 under the regular and loss scenarios, respectively. The capital costs were $676,200 and $733,000 under the regular and loss scenarios, respectively. The results showed a payback period of less than two years, regardless of scenario or PV technology, and the facilities will always remain profitable in the forward years, which are significantly promising results. The model eventually produced a stable supply of byproducts from c-Si PV, regardless of the instability and non-linearity in the generated c-Si PV wastes. Furthermore, the total PV waste generated from all the available CdTe PV projects in UAE accumulated to 68,180 tonnes. The model generated results from 2030 (operation-starting year) until 2075 (last waste generating year). However, the model showed that the annual dismantling capacities of the PVWMC were 1491 and 2123 tonnes under the regular and loss scenarios, respectively. The average annual profits were $765,421 and $758,174 under the regular and loss scenarios, respectively. The capital costs were $340,060 and $420,376 under the regular and loss scenarios, respectively. Similar to that of the c-Si PV, the model produced a stable supply of byproducts from CdTe PV, regardless of the CdTe PV waste generation's instability and non-linearity.

With the right adjustments to Equation (7) and its related details, the model can even be used in circular economies of non-PV products within the same PV system or beyond it within hybrid renewable energy product sustainability management, from cables, inverters, storage systems or batteries, and other supportive electronic devices. Additionally, the model can be used in comparing the feasibility of industrial symbiosis in PV-manufacturing nations and test if it can compete with the revenues feeding the local and global PV manufacturing industries. The model assumes that all materials will be sold to local non-PV-manufacturing industries, and existing global-, MENA-, and UAE- awareness driven by cost-saving drives the potential of industrial symbiosis and assures that such assumption is not far from reality. Though nevertheless, future works should validate this assumption locally via targeted buyer surveys, small pilot offtake contracts, and assessment of regulatory incentives. Additionally, alternative outcomes (e.g., lack of local demand due to low prices of virgin feedstock or high logistics costs) should be modelled and mitigated by supply aggregation or value-added processing, while taking into consideration the different dismantling techniques producing varying qualities of materials for each PV technology.

For UAE specific limitations, there are no manufacturing facilities in UAE that can benefit from the secondary market Silver, Tin, Lead, Cadmium, or Tellurium. Therefore, they were not included as a dedicated and separate stored output, despite their efficient dismantling potential. Instead, they were added to other byproducts separately stored with recoverable wastes. This is a purely UAE related limitation that only affects the way results are presented but it is completely addressed in the model as shown in Table 5 with each material's composition that was used in the model. The CdTe PV modules have aluminum and silicon within them, but the chosen dismantling processes do not separate them due to development shortage and low material recovery efficiency. Several researchers have worked on processes to recover a single byproduct, but not together simultaneously. The processes described in this work have proved to be the most efficient, recovering the materials' majority. The model is generic, flexible, and gives specific decisions for the waste management plans, even for nations with larger PV capacities. If modified correctly for decentralization, the model can be globalized to find the best supply chain network configuration on an international scale. The model's decentralization would be done through binary variables deciding if the PV waste coming from project p should go to the PVWMC c, and a weighing variable would be needed to distribute the waste of each project to the closest PVWMCs. The objective function would be the summation over all PVWMCs of a model similar to the one proposed in this work. On a micro scale, it is

advised to optimize a combined dismantling process, that simultaneously dismantles multiple PV technologies. Furthermore, automation planning for internal processes can be done with a similar optimization model through economic feasibility. The aggregated costs addressed in the model to represent the environmental and sustainability impacts can be further extended with more details in a multi-objective setting that design the processes of securing energy and water as well as carbon management, through power plants, desalination technologies, and carbon capture or fumes filters, respectively, while taking into consideration all operational and strategic consequences. The development of the model necessitates access to precise information and data concerning the most current dismantling technologies and machinery. Subsequently, the principal variables within the model will encompass the distinct inputs and outputs associated with each machine. For an even more efficient implementation of the sustainability's repurpose principle or IS, it is advised to compare the outputs of the dismantling processes with specific information on the inputs of each product's manufacturing process, not just raw vs. secondary materials-refining. Future works can now study the parameters' variability like the fluctuations of dismantling efficiencies, depending on waste state and machines' age. It is advisable to develop an additional mathematical model aimed at investigating the fluctuating costs associated with incoming PV waste over time and in relation to quality. For instance, PV modules deemed waste, yet comprising components in satisfactory condition, are expected to command higher prices compared to modules that have undergone multiple cycles of reuse, despite both being non-operational. This discrepancy underscores the need to consider various factors such as module age, technology, prevailing weather conditions, among others, as each can influence the technical state of individual components within the PV module. Consequently, a comprehensive understanding of these dynamics is crucial for accurately assessing the economic implications of PV waste management practices.

Author Contributions

M.K.H.R.: conceptualization, data curation, formal analysis, methodology, validation, visualization, writing—original draft; C.S.: conceptualization, supervision, visualization, writing—reviewing and editing. All authors have read and agreed to the published version of the manuscript.

Data Availability Statement

The authors confirm that the data supporting the findings of this study are available within the article.

Conflicts of Interest

The authors declare no conflict of interest.

Use of AI and AI-Assisted Technologies

No AI tools were utilized for this paper.

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