

# **MODELING AND ANALYSIS OF MANAGEMENT OF SOLAR PANEL E-WASTE: A CIRCULAR ECONOMY PERSPECTIVE**

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**NEW DELHI-110016, INDIA**

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# **MODELING AND ANALYSIS OF MANAGEMENT OF SOLAR PANEL E-WASTE: A CIRCULAR ECONOMY PERSPECTIVE**

by

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## CERTIFICATE

The Thesis entitled “Modeling and analysis of management of solar panel e-waste: a circular economy perspective”, being submitted by Mr. Ayush Gautam to the Indian Institute of Technology Delhi, for the award of the degree of Doctor of Philosophy (Ph.D.) is a record bona fide research work carried out by him. He has worked under my guidance and supervision and has fulfilled the requirements for the submission of this thesis, which has attained the standard required for a Ph.D. degree from the Indian Institute of Technology Delhi. The results presented in this thesis have not been submitted elsewhere for the award of any degree or diploma.

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## ABSTRACT

India has an abundance of solar energy to a tune of around 750 GW. Hence, the technology that converts sunlight into electricity and its ecosystem, which is dominated by solar photovoltaic (PV), will probably rule the future. In the recent past, technological advances in the solar PV sector have accelerated, leading to managerial problems for end-of-life (EOL) disposal of solar PV e-waste. EOL panels' waste management and secondary raw material extraction become important to conserve resources and reduce production costs. Developed countries like the US, Germany, Japan, and many others have already started emphasizing on solar photovoltaic e-waste, whereas India is focussing only on photovoltaic panel installations with little concern on e-waste. In this research, an empirical estimation shows that solar PV installations in India will generate 347.5 GW by 2030.

The present research deals with the circular economy (CE), circular supply chain (CSC), and electronic waste management with a special focus on solar panel waste and their balance of system (BOS). Firstly, this study undertakes an assessment of the magnitude of the issue in India, using a forecasting model that projects the amount of waste generated by EOL solar PV panels and its balance of system (BOS) using the Weibull reliability function for panel failure. The study also estimates the amount of raw material recovered after recycling to contribute to the circular economy of EOL PV. The present research discussed establishing a monitoring system to handle this much e-waste, for which immediate efforts are required to develop a dedicated circular economy-based reverse supply chain for PV e-waste.

In continuation, for the strategic management of EOL solar PV e-waste generated in developing countries like India, the economy and weight share of twenty-one metals present in the solar PV systems have been discussed in the research. In the next objective, the research provides an

architectural framework for the realistic management of EOL solar PV using the CE concept. Research focuses on developing an organized recycling infrastructure in India for EOL e-waste, with a special focus on twenty-one metals present in EOL solar PV and its balance of systems (BOS) using the Pareto analysis, Criticality analysis, Material flow analysis, and Gravity. The research used material-flow-analysis for managing the e-waste as per the requirement of the circular economy for designing recycling, remanufacturing, refurbishing (RRR) strategy, and assessment of resource-efficient regulations.

In the next objective, the operational decisions in the management of solar panel e-waste are analysed by the identification and categorization of operational inhibitors for EOL solar PV management. Interrelationships among operational inhibitors to CE-based e-waste management in emerging economies established using grey DEMATEL technique. A multi-stakeholder perspective for End-of-life solar PV used is in decision making. Further, an Agent-Based circular economy business model (CEBM) for applying CE concepts in reverse SC management of EOL e-waste has been developed. The study redefines the role of Producer responsibility organizations (PRO) as developing countries do not have producers in the country. The CEBM was validated by applying real-world data in three different scenarios and by cost-benefit analysis. The research proposes a policy change insight in the Extended producer responsibility (EPR) scheme, where the producer must also be responsible for RRR of EOL e-waste in addition to recycling in developing countries.

The research shed light on maximizing resource efficiency by creating facilities for a circular economy-based supply chain to handle the massive e-waste generated by solar PV panels in India. Results show that India expects 2.95 million tonnes of waste from EOL solar PV and its BOS between 2020 and 2047. This waste is worth 645 billion USD, out of which 70% of the waste (worth 452 billion USD) could be recovered only by recycling, while revenue of 779 billion can be generated if we use the concept of the circular economy. Waste generated in

2021 itself sufficient for running 229 Recycling plant of 1850 tone with a gross profit of \$440933 while with the CE (Recycling, remanufacturing, Reuse) 23 Remanufacturing plant, 149 refurbish plant and 57 recycling plant can be run with profit gross profit of \$58779. This study address CE by expanding the conventional forward and reverse supply chain analysis to CSC design and providing the policy modifications for better implications of the CE. The study can act as a database for future researchers to explore the area. Proposed CEBM can help stakeholders to understand and apply circular economy for EOL solar PV and other e-waste in developing countries of by modifying the current policies of EPR and PRO.

**Keywords:** Circular-Economy, Circular supply chain, solar PV, e-waste, Recycling

## सार

भारत में लगभग 750 GW की सौर ऊर्जा की प्रचुरता है। इसलिए, वह तकनीक जो सूर्य के प्रकाश को बिजली और उसके पारिस्थितिकी तंत्र में परिवर्तित करती है, जिसमें सौर फोटोवोल्टिक (पीवी) का प्रभुत्व है, शायद भविष्य पर शासन करेगी। हाल के दिनों में, सौर पीवी क्षेत्र में तकनीकी प्रगति में तेजी आई है, जिससे सौर पीवी ई-कचरे के एंड-ऑफ-लाइफ (ईओएल) निपटान के लिए प्रबंधकीय समस्याएं पैदा हो गई हैं। संसाधनों के संरक्षण और उत्पादन लागत को कम करने के लिए ईओएल पैनलों का अपशिष्ट प्रबंधन और द्वितीयक कच्चे माल की निकासी महत्वपूर्ण हो जाती है। अमेरिका, जर्मनी, जापान और कई अन्य जैसे विकसित देशों ने पहले से ही सौर फोटोवोल्टिक ई-कचरे पर जोर देना शुरू कर दिया है, जबकि भारत केवल फोटोवोल्टिक पैनल प्रतिष्ठानों पर ध्यान केंद्रित कर रहा है, जिसमें ई-कचरे पर कोई चिंता नहीं है। इस शोध में, एक अनुभवजन्य अनुमान से पता चलता है कि भारत में सौर पीवी प्रतिष्ठान 2030 तक 347.5 GW उत्पन्न करेंगे।

वर्तमान शोध सर्कुलर-इकोनॉमी (सीई), सर्कुलर सप्लाई चेन (सीएससी) और इलेक्ट्रॉनिक वेस्ट मैनेजमेंट से संबंधित है, जिसमें सोलर पैनल वेस्ट और उनके बैलेंस ऑफ सिस्टम (बीओएस) पर विशेष ध्यान दिया जाता है। सबसे पहले, यह अध्ययन एक पूर्वानुमान मॉडल का उपयोग करके भारत में मुद्दे की भयावहता का आकलन करता है, जो पैनल विफलता के लिए वीबुल विश्वसनीयता फ़ंक्शन का उपयोग करके ईओएल सौर पीवी पैनलों और इसके संतुलन प्रणाली (बीओएस) द्वारा उत्पन्न कचरे की मात्रा को प्रोजेक्ट करता है। अध्ययन में ईओएल पीवी की सर्कुलर अर्थव्यवस्था में योगदान करने के लिए पुनर्चक्रण के बाद बरामद कच्चे माल की मात्रा का भी अनुमान लगाया गया है। वर्तमान शोध में इतने ई-कचरे को संभालने के लिए एक निगरानी प्रणाली स्थापित करने पर चर्चा की गई, जिसके लिए पीवी ई-कचरे के लिए एक

समर्पित सर्कुलर इकोनॉमी-आधारित रिवर्स सप्लाई चेन विकसित करने के लिए तत्काल प्रयासों की आवश्यकता है।

निरंतरता में, भारत जैसे विकासशील देशों में उत्पन्न ईओएल सौर पीवी ई-कचरे के रणनीतिक प्रबंधन के लिए, अनुसंधान में सौर पीवी प्रणालियों में मौजूद इक्कीस धातुओं की अर्थव्यवस्था और वजन हिस्सेदारी पर चर्चा की गई है। अगले उद्देश्य में, अनुसंधान सीई अवधारणा का उपयोग करते हुए ईओएल सौर पीवी के यथार्थवादी प्रबंधन के लिए एक वास्तुशिल्प ढांचा प्रदान करता है। अनुसंधान ईओएल ई-कचरे के लिए भारत में एक संगठित पुनर्चक्रण बुनियादी ढांचे के विकास पर केंद्रित है, जिसमें ईओएल सौर पीवी में मौजूद इक्कीस धातुओं और पारेतो विश्लेषण, महत्वपूर्ण विश्लेषण, सामग्री प्रवाह विश्लेषण, गुरुत्वाकर्षण का उपयोग करते हुए सिस्टम के संतुलन (बीओएस) पर विशेष ध्यान दिया गया है। विश्लेषण और लागत लाभ विश्लेषण। अनुसंधान ने रीसाइक्लिंग, रीमैन्युफैक्चरिंग, रीफर्बिशिंग (आरआरआर) रणनीति और संसाधन कुशल नियमों के आकलन के लिए परिपत्र अर्थव्यवस्था की आवश्यकता के अनुसार ई-कचरे के प्रबंधन के लिए सामग्री-प्रवाह-विश्लेषण का उपयोग किया।

ईओएल सौर पीवी प्रबंधन के लिए परिचालन अवरोधकों की पहचान और वर्गीकरण द्वारा विश्लेषण किए गए सौर पैनल ई-कचरे के प्रबंधन में परिचालन निर्णय। उभरती अर्थव्यवस्थाओं में सीई आधारित ई-कचरा प्रबंधन के लिए परिचालन अवरोधकों के बीच अंतर्संबंध ग्रे DEMATEL तकनीक का उपयोग करके स्थापित किया गया। उपयोग किए गए एंड-ऑफ-लाइफ सोलर पीवी के लिए एक बहु-हितधारक परिप्रेक्ष्य निर्णय लेने में है। इसके अलावा, ईओएल ई-कचरे के श्रद्धेय एससी प्रबंधन में सीई अवधारणाओं को लागू करने के लिए एजेंट आधारित सर्कुलर इकोनॉमी बिजनेस मॉडल (सीईबीएम) विकसित किया गया है। अध्ययन निर्माता जिम्मेदारी संगठनों (पीआरओ) की भूमिका को फिर से परिभाषित करता है क्योंकि विकासशील देशों में देश में उत्पादक नहीं होते हैं। सीईबीएम ने तीन अलग-अलग परिदृश्यों में वास्तविक दुनिया के डेटा को लागू करके मान्य किया। अनुसंधान विस्तारित उत्पादक जिम्मेदारी

(ईपीआर) योजना में एक नीति परिवर्तन अंतर्दृष्टि का प्रस्ताव करता है जहां उत्पादक को विकासशील देश में रीसाइक्लिंग के अलावा ईओएल ई-कचरे के आरआरआर के लिए भी जिम्मेदार होना चाहिए।

शोध भारत में सौर पीवी पैनलों द्वारा उत्पन्न बड़े पैमाने पर ई-कचरे को संभालने के लिए एक परिपत्र अर्थव्यवस्था-आधारित आपूर्ति श्रृंखला के लिए सुविधाओं का निर्माण करके संसाधन दक्षता को अधिकतम करने पर प्रकाश डालता है। परिणामों से पता चलता है कि भारत को 2020 और 2047 के बीच ईओएल सोलर पीवी और इसके बीओएस से 295 मिलियन टन कचरे की उम्मीद है। यह अपशिष्ट 645 बिलियन अमरीकी डालर का है, जिसमें से 70% अपशिष्ट (452 बिलियन अमरीकी डालर मूल्य) को केवल पुनर्चक्रण द्वारा ही पुनर्प्राप्त किया जा सकता है। जबकि सर्कुलर इकोनॉमी की अवधारणा का उपयोग करने पर 779 बिलियन का राजस्व उत्पन्न किया जा सकता है। 2021 में उत्पन्न अपशिष्ट 440933 डॉलर के सकल लाभ के साथ 1850 टन के 229 पुनर्चक्रण संयंत्र को चलाने के लिए पर्याप्त है, जबकि सीई (पुनर्चक्रण, पुनः निर्माण, पुनः उपयोग) के साथ 23 पुनर्विनिर्माण संयंत्र, 149 नवीनीकरण संयंत्र और 57 पुनर्चक्रण संयंत्र लाभ सकल लाभ के साथ चलाए जा सकते हैं 58779\$ का। यह अध्ययन सीई को सीएससी डिजाइन में पारंपरिक फॉरवर्ड और रिवर्स सप्लाई चैन विश्लेषण का विस्तार करके संबोधित करता है और सीई के बेहतर प्रभाव के लिए नीति संशोधन प्रदान करता है। अध्ययन क्षेत्र की खोज के लिए भविष्य के शोधकर्ताओं के लिए डेटाबेस के रूप में कार्य कर सकता है। प्रस्तावित सीईबीएम ईपीआर और पीआरओ की वर्तमान नीतियों को संशोधित करके विकासशील देशों में ईओएल सौर पीवी और अन्य ई-कचरे के लिए सर्कुलर अर्थव्यवस्था को समझने और लागू करने में हितधारकों की मदद कर सकता है।

कीवर्ड: सर्कुलर-इकोनॉमी, सर्कुलर सप्लाई चैन, सोलर पीवी, ई-वेस्ट, रीसाइक्लिंग

# TABLE OF CONTENTS

CERTIFICATE	i
ACKNOWLEDGEMENTS	ii
ABSTRACT	iv
संर	vii
TABLE OF CONTENTS	x
LIST OF FIGURES	xvi
LIST OF TABLES	xviii
LIST OF INDICES, VARIABLES AND PARAMETERS	xx
LIST OF ABRREVIATIONS	xxii
<b>1. CHAPTER 1</b>	<b>1</b>
<hr/>	
INTRODUCTION TO THE STUDY	1
1.1 INTRODUCTION	1
1.1.1 SOLAR PV INSTALLATION: - BACKGROUND OF STUDY	2
1.2 MOTIVATION OF RESEARCH	4
1.3 CIRCULAR SUPPLY CHAIN FOR EOL SOLAR PV WASTE	5
1.3.1 CIRCULAR ECONOMY	5
1.3.2 CIRCULAR SUPPLY CHAIN	6
1.4 RESEARCH OVERVIEW	7
1.5 SCOPE OF RESEARCH	8
1.6 CONTEXT OF THE RESEARCH FOR SMES	9
1.7 RESEARCH FOCUS	10

<b>1.8 ORGANISATION OF THESIS</b>	<b>11</b>
<b>1.9 CHAPTER SUMMARY</b>	<b>14</b>
<b>2. CHAPTER 2</b>	<b>15</b>
<b>LITERATURE REVIEW</b>	<b>15</b>
<b>2.1 INTRODUCTION</b>	<b>15</b>
<b>2.2 LITERATURE ON CIRCULAR ECONOMY</b>	<b>19</b>
<b>2.3 END-OF LIFE SOLAR PANEL E-WASTE MANAGEMENT</b>	<b>20</b>
2.3.1 LITERATURE ON E-WASTE MANAGEMENT AND CIRCULAR ECONOMY	21
<b>2.4 RESEARCH TOOL</b>	<b>24</b>
<b>2.5 RESEARCH GAPS</b>	<b>26</b>
<b>2.6 RESEARCH QUESTION</b>	<b>27</b>
<b>2.7 RESEARCH OBJECTIVES</b>	<b>28</b>
<b>2.8 CHAPTER SUMMARY</b>	<b>29</b>
<b>3. CHAPTER 3</b>	<b>31</b>
<b>DEVELOPING AN APPROACH TOWARDS ESTIMATION OF SOLAR PANEL E-WASTE</b>	<b>31</b>
<b>3.1 INTRODUCTION</b>	<b>31</b>
<b>3.2 DATA AND METHODS</b>	<b>32</b>
3.2.1 ESTIMATION OF ANNUAL SOLAR PANEL INSTALLATION IN INDIA FROM 1992 TO 2030	34
3.2.2 DETERMINE THE DIFFERENT TECHNOLOGIES OF SOLAR PV AND THEIR MARKET SHARE	36
3.2.3 DETERMINE THE COMPOSITION AND ESTIMATE THE AMOUNT OF MATERIAL CONTAINED IN A SOLAR PANEL AND ITS BOS FOR 1 GW POWER INSTALLED	36
3.2.4 CALCULATE THE PV MODULE DEGRADATION RATE IN DIFFERENT SCENARIOS	39
3.2.5 ESTIMATE THE LOSS OF SOLAR POWER EVERY YEAR UNTIL 2047	41

3.2.6 ESTIMATE THE MASS-GENERATED WASTE OF EACH MATERIAL IN THE SOLAR PANEL SYSTEM	41
3.2.7 RECYCLING AND ECONOMIC ANALYSIS	42
<b>3.3 RESULTS</b>	<b>43</b>
3.3.1 MATERIAL REQUIREMENT FOR THE ESTIMATED SOLAR ENERGY DEMAND	43
3.3.2 WASTE AND MATERIAL INVENTORY	44
3.3.3 RECYCLING AND ECONOMIC ANALYSIS OF METAL INVENTORY	50
3.3.4 SENSITIVITY ANALYSIS	52
<b>3.4 DISCUSSION</b>	<b>55</b>
<b>3.5 CHAPTER SUMMARY</b>	<b>57</b>
<b>4. CHAPTER 4</b>	<b>59</b>
<hr/>	
<b>STRATEGIES TOWARDS MANAGEMENT OF SOLAR PANEL E-WASTE</b>	<b>59</b>
<b>4.1 INTRODUCTION</b>	<b>59</b>
<b>4.2 DATA AND METHODS</b>	<b>59</b>
4.2.1 WASTE CLASSIFICATION	60
4.2.2 MATERIAL FLOW ANALYSIS	61
4.2.3 RECYCLING FACILITY LOCATION	63
<b>4.3 ANALYSIS AND RESULTS</b>	<b>66</b>
4.3.1 CLASSIFICATION OF METALS BASED ON MASS AND ECONOMIC SHARE	66
4.3.2 MATERIAL FLOW ANALYSIS FOR EOL SOLAR PV WASTE	68
4.3.3 DESIGNING A REVERSE SUPPLY CHAIN FOR EOL SOLAR PV WASTE	72
<b>4.4 DISCUSSION</b>	<b>73</b>
<b>4.5 CHAPTER SUMMARY</b>	<b>75</b>
<b>5. CHAPTER 5</b>	<b>77</b>
<hr/>	

<b>A FEW OPERATIONAL DECISIONS IN THE MANAGEMENT OF SOLAR PANEL E-WASTE</b>	<b>77</b>
<b>5.1 INTRODUCTION</b>	<b>77</b>
5.1.1 THE MOTIVATION AND PROPOSED CONTRIBUTION	78
<b>5.2 LITERATURE REVIEW</b>	<b>79</b>
<b>5.3 THE GREY-DEMATEL METHODOLOGY</b>	<b>85</b>
<b>5.4 RESULTS AND DISCUSSION</b>	<b>91</b>
5.4.1 MANAGERIAL IMPLICATIONS	99
<b>5.5 CHAPTER SUMMARY</b>	<b>100</b>
<b>6. CHAPTER 6</b>	<b>102</b>
<hr/>	
<b>CIRCULAR ECONOMY BUSINESS MODEL OF E-WASTE MANAGEMENT</b>	<b>102</b>
<b>6.1 INTRODUCTION</b>	<b>102</b>
<b>6.2 MODEL DEVELOPMENT</b>	<b>102</b>
6.2.1 EXTENDED PRODUCER RESPONSIBILITY (EPR)	105
6.2.2 PRODUCER RESPONSIBILITY ORGANIZATION (PRO)	105
6.2.2.1 ROLE OF PRO	106
<b>6.3 CEBM MODEL</b>	<b>107</b>
6.3.1 CEBM FOR EOL SOLAR PV E-WASTE	108
<b>6.4 CEBM AND ITS EXPLANATION</b>	<b>111</b>
6.4.1 THEORETICAL EXPLANATION OF THE CIRCULAR SUPPLY CHAIN IN THE MODEL –	112
6.4.2 CALCULATION OF THE MODEL	116
<b>6.5 CHAPTER SUMMARY</b>	<b>122</b>
<b>7. CHAPTER 7</b>	<b>124</b>
<hr/>	
<b>MODEL VALIDATION</b>	<b>124</b>

<b>7.1 INTRODUCTION</b>	<b>124</b>
<b>7.2 METHODS</b>	<b>125</b>
7.2.1 COST BENEFIT ANALYSIS	127
<b>7.3 CASE STUDY DATA</b>	<b>131</b>
<b>7.4 RESULT AND DISCUSSION</b>	<b>137</b>
<b>7.5 CHAPTER SUMMARY</b>	<b>148</b>
<b>8. CHAPTER 8</b>	<b>149</b>
<hr/>	
<b>SYNTHESIS AND CONCLUSION</b>	<b>149</b>
<b>8.1 INTRODUCTION</b>	<b>149</b>
<b>8.2 MAJOR RESEARCH CONTRIBUTIONS</b>	<b>152</b>
8.2.1 RECOMMENDATION FOR IMPLEMENTING A CIRCULAR ECONOMY FOR EOL SOLAR PV IN INDIA	154
8.2.2 RECOMMENDATION FOR IMPLEMENTING A CIRCULAR ECONOMY IN SMES FOR EOL SOLAR PV E-WASTE	155
<b>8.3 MANAGERIAL AND POLICY IMPLICATIONS OF THE PRESENT RESEARCH</b>	<b>155</b>
8.3.1 CONTRIBUTION USEFUL TO ACADEMIA	157
8.3.2 IMPLICATIONS FOR POLICY MAKERS	157
8.3.3 CONTRIBUTION FOR PRACTITIONERS	159
<b>8.4 LIMITATIONS AND FUTURE SCOPE OF THE RESEARCH</b>	<b>160</b>
8.4.1 THEORETICAL RECOMMENDATIONS FOR FUTURE STUDIES	160
8.4.2 FUTURE DIRECTION OF RESEARCH	160
8.4.3 LIMITATIONS OF RESEARCH	161
<b>8.5 CHAPTER SUMMARY</b>	<b>162</b>
<b>REFERENCES</b>	<b>163</b>
<b>APPENDICES</b>	<b>179</b>
Appendix A.1: Market share of each technology and PV waste generation year (Domínguez & Geyer, 2017)	179

Appendix A.2: Format of Questionnaire for conducting the survey.	180
<b>PUBLICATIONS FROM THE THESIS</b>	<b>193</b>
<b>PROFILE OF THE RESEARCHER</b>	<b>194</b>

# LIST OF FIGURES

FIGURE 1-1 ORGANIZATION OF THESIS .....	13
FIGURE 2-1 LITERATURE FRAMEWORK .....	16
FIGURE 3-1 METHODOLOGY FLOW CHART FOR ESTIMATING RECOVERED MATERIALS FROM SOLAR PV INSTALLATION .....	33
FIGURE 3-2 TREND OF SOLAR POWER (GW) INSTALLATION IN INDIA BY 2047 (MNRE, 2018; NCPRE & NISE, 2017; TERI, 2015) .....	35
FIGURE 3-3 WEIBULL CUMULATIVE DISTRIBUTION FUNCTION FOR REGULAR LOSS AND EARLY LOSS FOR THE GIVEN PARAMETERS (WECKEND ET AL., 2016).....	40
FIGURE 3-4 ESTIMATED NUMBER OF MODULES REQUIRED FOR PV INSTALLATION BY 2030 .....	44
FIGURE 3-5 COMPARISON OF ESTIMATED SOLAR PV PANEL EOL WASTE WITH IRENA WASTE BY 2047 .....	45
FIGURE 3-6 YEAR-WISE PV REPOWERING REQUIREMENT DUE TO DIFFERENT LOSSES .....	46
FIGURE 3-7 ESTIMATED CUMULATIVE EOL PV SYSTEM WASTE (MILLION TONNES) FROM 1992 TO 2047.....	46
FIGURE 3-8 ESTIMATED MASS SHARE OF COMPONENTS AND TECHNOLOGY IN EOL PV PANELS BETWEEN 2020 AND 2047 .....	47
FIGURE 3-9 ESTIMATED MASS SHARE OF MATERIALS IN EOL SOLAR PV SYSTEMS BETWEEN 2020 AND 2047 .....	47
FIGURE 3-10 TRENDS OF SILVER MASS AS WASTE GENERATED AND RECOVERED BY 2047 AND REQUIRED BY 2030 .....	48
FIGURE 3-11 TRENDS OF GOLD MASS AS WASTE GENERATED AND RECOVERED BY 2047 AND REQUIRED BY 2030 .....	49
FIGURE 3-12 DIFFERENT TOXIC METALS GENERATED BY 2047 BY EOL SOLAR PV SYSTEMS .....	49
FIGURE 3-13 TRENDS SHOWING CRITICAL MATERIAL WASTE GENERATED BY 2047 AND CRITICAL MATERIAL REQUIRED BY 2030.....	49
FIGURE 3-14 ESTIMATED ECONOMIC SHARE OF METALS IN PV SYSTEM WASTE BETWEEN 2020 AND 2047 .....	50
FIGURE 4-1 STATE-WISE CLUSTERING AND SOLAR POTENTIAL IN INDIA.....	64
FIGURE 4-2 CLASSIFICATION OF METALS BASED ON MASS AND ECONOMIC SHARE .....	67
FIGURE 4-3 MFA FOR RECYCLING OF E-WASTE.....	69
FIGURE 4-4 MFA CLOSED-LOOP SUPPLY CHAIN .....	70
FIGURE 4-5 MFA FOR CIRCULAR SUPPLY CHAIN.....	71
FIGURE 4-6 LOCATION OF COLLECTION AND RECYCLING CENTRES .....	73
FIGURE 5-1 FLOW CHART OF GREY DEMATEL CASUAL ANALYSIS .....	80
FIGURE 5-2 QUADRANT MATRIX OF DEMATEL .....	90

FIGURE 5-3 DIAGRAPH FOR E-WASTE COLLECTOR PERSPECTIVE.....	96
FIGURE 5-4 DIAGRAPH FOR RECOVERY AGENTS' PERSPECTIVE.....	96
FIGURE 5-5 DIAGRAPH FOR POLICYMAKER PERSPECTIVE.....	97
FIGURE 5-6 DIAGRAPH FOR OVERALL PERSPECTIVE.....	97
FIGURE 5-7 STAKEHOLDERS EUCLIDIAN DISTANCE.....	99
FIGURE 6-1 THE CIRCULAR ECONOMY VALUE JOURNEY ( <a href="https://www.boardofinnovation.com/circular-economy-business-models-explained/">HTTPS://WWW.BOARDOFINNOVATION.COM/CIRCULAR-ECONOMY-BUSINESS-MODELS-EXPLAINED/</a> ).....	108
FIGURE 6-2 FRAMEWORK FOR THE CIRCULAR SUPPLY CHAIN OF E-WASTE IN DEVELOPING.....	112
FIGURE 6-3 FLOW CHART OF AGENT'S DISCRETE EVENT.....	115
FIGURE 6-4 INPUTS AND OUTPUT OF AGENTS.....	118
FIGURE 6-5 TIME SEQUENCE DIAGRAM FOR THE INTERACTION OF AGENTS.....	121
FIGURE 7-1 RECYCLING ONLY FLOW OF SOLAR PV E-WASTE.....	128
FIGURE 7-2 FLOW OF SOLAR PV E-WASTE AS PER CE.....	130
FIGURE 7-3 INFORMAL E-WASTE COLLECTION AND TREATMENT VILLAGE "SEELUMPUR VISIT".....	136
FIGURE 7-4 ECONOMY RECOVERED WITH AND WITHOUT CE.....	144
FIGURE 7-5 PERCENTAGE SHARE OF ECONOMY RECOVERED WITH AND WITHOUT CE.....	144
FIGURE 7-6 MASS RECOVERED WITH AND WITHOUT CE AND MASS SAVED WITH CE.....	145
FIGURE 7-7 MASS SAVED WHILE USING CONCEPTS OF CE.....	146
FIGURE 7-8 PERCENTAGE SHARE OF MASS RECOVERED WITH AND WITHOUT CE AND MASS SAVED WITH CE.....	146
FIGURE 7-9 PICTORIAL PRESENTATION OF SCENARIO ANALYSIS FOR MODEL VALIDATION.....	147

# LIST OF TABLES

TABLE 2-1 STANDARD REPORTS USED FOR DATA COLLECTION AND LITERATURE REVIEW .....	16
TABLE 2-2 LITERATURE REVIEW OF WASTE MANAGEMENT USING MFA.....	25
TABLE 2-3 OBJECTIVES AND PROPOSED METHODOLOGY .....	29
TABLE 3-1 OVERVIEW AND PROJECTION OF SOLAR PV INSTALLED IN INDIA (GW .....	34
TABLE 3-2 SOLAR PANEL TECHNOLOGY CLASSIFICATION (ARORA ET AL., 2018) .....	36
TABLE 3-3 SPECIFICATIONS OF PV PANELS (DOMÍNGUEZ & GEYER, 2017, 2018; MAHMOUDI, HUDA, & BEHNIA, 2019; SANTOS & ALONSO-GARCÍA, 2018).....	37
TABLE 3-4 MASS OF ALL THE COMPONENTS IN SOLAR PV SYSTEM (TONNE/ GW) (DOMÍNGUEZ & GEYER, 2017, 2018; ITRPV, 2019; MAHMOUDI, HUDA, & BEHNIA, 2019; PAIANO, 2015; SANTOS & ALONSO-GARCÍA, 2018).....	38
TABLE 3-5 ESTIMATED INVENTORY REQUIRED FOR SOLAR PV INSTALLATION BY 2030 .....	50
TABLE 3-6 ESTIMATED WEIGHT AND ECONOMIC SHARE OF METALS IN EOL PV SYSTEM WASTE GENERATED IN INDIA BETWEEN 2020 AND 2047 .....	53
TABLE 3-7 ESTIMATED POWER LOSS (GW), MATERIAL LOSS AND PRECIOUS METAL LOSS (TONNES) BETWEEN 2020 AND 2047 .....	54
TABLE 4-1 METAL COMPOSITION IN SOLAR PV SYSTEM (TONS/GW) (GAUTAM ET AL., 2021).....	61
TABLE 4-2 METALS' ESTIMATED ECONOMIC AND WEIGHT PERCENTAGE OF EOL PV SYSTEM WASTE GENERATED IN INDIA BETWEEN 2020 AND 2047 (DOMÍNGUEZ & GEYER, 2018; GAUTAM ET AL., 2021) .....	62
TABLE 4-3 CLUSTERING FOR EFFICIENT EOL SOLAR PV WASTE COLLECTION.....	65
TABLE 5-1 LIST OF INHIBITORS .....	81
TABLE 5-2 EXPERT RESPONSE SCALE FOR GREY DEMATEL .....	86
TABLE 5-3 TRM FOR E-WASTE COLLECTOR PERSPECTIVE .....	92
TABLE 5-4 TRM FOR RECYCLER PERSPECTIVE .....	93
TABLE 5-5 TRM FOR POLICY MAKER PERSPECTIVE .....	94
TABLE 5-6 TRM FOR POLICY MAKER PERSPECTIVE.....	95
TABLE 5-7 COMPARATIVE ANALYSIS OF STAKEHOLDER'S PERSPECTIVE .....	98
TABLE 6-1 LITERATURE USED ABM MODEL FOR WASTE MANAGEMENT.....	109
TABLE 7-1 DATA FOR THE FAILURE OF PV PANELS AT PV PLANT.....	132

TABLE 7-2 CLASSIFICATION OF THE AMOUNT OF WASTE GENERATED BETWEEN 2020 TO 2047 FOR RRR. ....	132
TABLE 7-3 INPUT DATA FOR ECONOMIC ANALYSIS .....	137
TABLE 7-4 ECONOMY AND MASS (TON) RECOVERY OF METALS IN EOL SOLAR PV E-WASTE AFTER RRR.....	140
TABLE 7-5 SCENARIO ANALYSIS FOR MODEL VALIDATION .....	147
TABLE 8-1 OBJECTIVE WISE RESEARCH OUTCOME.....	151

## LIST OF INDICES, VARIABLES AND PARAMETERS

$x_i$	-	Amount on PV installed in year i
$u_{fj}$	-	Power loss in year j for fixed loss
i	-	The year of installation
j	-	The year of waste generation
t	-	Time duration in year
T	-	Average lifetime
Y	-	Shape factor
$u_{rt}$	-	The rate of power loss for regular loss after year t.
$u_{et}$	-	The rate of power loss for early loss after year t.
$U_{cj}$	-	Corrected power loss in year j
$U_{ej}$	-	Early power loss in year j
$\alpha$	-	Technology (out of Silicon-based, cdte, cigs)
$U_{rj}$	-	Regular power loss in year j
$W_{j\alpha}$	-	Solar panel WEEE in year j (tonne) by technology $\alpha$
w	-	Weight of solar panel composition in tonne/ GW for technology $\alpha$
p	-	Market share of technology $\alpha$
$r_e$	-	Opportunity cost
DCF	-	Discounted cash flow
NPV	-	Net present value
DCI	-	Discounted cash inflow
DCO	-	Discounted cash outflow
CI	-	Cash inflow

CO	-	Cash outflow
DPBT	-	Discounted payback period
InfR	-	Inflation rate
WACC	-	Capital weightage average capital cost
u	-	Unitary quantity
t	-	Time of cash flow

## LIST OF ABRREVATIONS

ABM	-	Agent based modeling
BOS	-	Balance of system
BTI	-	Bridge to India
CBA	-	Cost-benefit analysis
CE	-	Circular economy
CEBM	-	Circular economy business model
CI	-	Cash inflow
CLSC	-	Closed-loop supply chain
CLSC	-	Closed-loop supply chain
CO	-	Cash outflow
CSC	-	Circular supply chain
DCF	-	Discounted cash flow
DCI	-	Discounted cash inflow
DCO	-	Discounted cash outflow
DEMATEL	-	Decision Making Trial and Evaluation Laboratory
DPBT	-	Discounted payback period

EESL	-	Energy Efficiency Services Limited
EOL	-	End-of-life
EPR	-	Extended producer responsibility
EU REI	-	European Union's Resource Efficiency Initiative
EVA	-	Ethylene vinyl acetate
EVA	-	Ethylene vinyl acetate
FL	-	Forward Logistics
IEA	-	International Energy Agency
InfR	-	Inflation rate
IREDA	-	Indian Renewable Energy Development Agency Limited
IRENA	-	International Renewable Energy Agency
ITRPV	-	International Technology Roadmap for Photovoltaic
JBR	-	Journal of Business research
LSCM	-	Logistics and Supply Chain Management
MCDM	-	Multi-Criteria Decision Making
MFA	-	Material flow analysis
MILP	-	Mixed Integer Linear Programming
MNRE	-	Ministry of New and Renewable Energy
NCPRE	-	National Centre for Photovoltaic Research and Education

NETRA	-	NTPC Energy Technology Research Alliance
NISE	-	National Institute of Solar Energy
NPV	-	Net present value
NSEFI	-	National Solar Energy Federation of India
PRO	-	Producer responsibility organization
PSS	-	Product Service System
PV	-	Photovoltaic
RL	-	Reverse logistic
RL	-	Reverse Logistics
RM	-	Recycled material
RRR	-	Recycling, refurbishing, and remanufacturing
SC	-	Supply chain
SCM	-	Supply chain management
SEARC	-	Solar energy research advisory council
SECI	-	Solar Energy Corporation of India
SERRIUS	-	Solar Energy Research Institute for India and the United State
SLR	-	Systematic Literature Review
SMEs	-	small and medium-sized enterprises
SPC	-	Sustainable Production and Consumption

- STAN - substance flow analysis
- TERI - The Energy Resource Institute's
- UTM - Universal Transverse Mercator
- WACC - Capital weight age average capital cost
- WEEE - waste electrical and electronic equipment