MSc Program
Renewable Energy Systems

A Sustainable Approach For Managing The End-of-Life Phase Of Photovoltaic Systems

A Master's Thesis submitted for the degree of
"Master of Science"

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Vienna, October 24, 2017

Affidavit

I, **ROXANA L. PREDOIU**, hereby declare

1. that I am the sole author of the present Master’s Thesis, "A Sustainable Approach For Managing The End-of-Life Phase Of Photovoltaic Systems", 107 pages, bound, and that I have not used any source or tool other than those referenced or any other illicit aid or tool, and
2. that I have not prior to this date submitted this Master’s Thesis as an examination paper in any form in Austria or abroad.

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Abstract

The Paris Agreement on Climate Change was adopted (2015) by more than 190 countries and it focuses on limiting the increase in global average temperature well below 2°C above the pre-industrial levels. Essentially, this represents an unprecedented, global agreement to meaningful action in order to gradually transform the world's energy sector, and to mitigate anthropogenic climate change, by implementing clean, low-carbon energy sources. Also in 2015, countries adopted a set of 17 Sustainable Development Goals to end poverty, protect the planet, and ensure prosperity for all as part of a new United Nations sustainable development agenda.

Despite certain challenges, it is generally considered that clean energy technologies are capable of meeting the global energy demands, supporting the world to transition towards decarbonized energy systems and to mitigate climate change issues. Solar Photovoltaic (PV) technology has been one of the fastest growing clean energy industries over the last two decades, reaching 300 GW installed capacity by 2016. Assuming an average PV Panel lifetime of 30 years, IEA PVPS and IRENA have estimated in 2016 that considerable amounts of PV Panel Waste will start occurring within the next decade, and will continue to upsurge up until 2050 (and after). Quickly growing amounts of PV Panel Waste could pose serious environmental challenges, due to their expected amounts, and also due to their chemical composition, which includes certain hazardous elements.

This thesis presents the current status of the PV technologies, future PV technology trends, the evolution of global PV electricity production, and the expected streams of PV Panel Waste. It also applies a Systems Thinking, integrative approach, to identify and discuss concrete options in order to manage, in a sustainable manner, the overall PV life cycle, focusing primarily on the end-of-life phase. Adopting the Reduce-Reuse-Recycle paradigm and implementing Industry 4.0 concepts will fortify and accelerate the world's transition towards a circular economy, fostering resource use efficiency and increased productivity. Moreover, it will contribute to achieving several of the 17 UN Sustainable Development Goals, by generating economic growth and creating new job opportunities while safeguarding the environment.

A linear programming model has been developed for this thesis, in order to support the optimal decision process, concerning the allocation of PV Panel Waste amounts to PV Recycling Centers, in a manner that minimizes environmental costs due to transport and logistics associated with the PV end-of-life management, while fostering a competitive business environment.

Key Words: PV Recycling; Systems Thinking; Linear Optimization Model; SDG; Industry 4.0; Reduce-Reuse-Recycle; Blockchain; IoT; Preventive Maintenance;

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1 Introduction

The continuously growing global energy demand, fulfilled by an energy sector which has been relying mostly on fossil fuels (over 80% at the beginning of the last decade [21], has been indisputably the source of more than two thirds of global greenhouse-gas emissions, thus, a main contributor to one of the most serious environmental issues in Earth's history: anthropogenic climate change.

The historic Paris Treaty on Climate Change (2016), with its central goal of limiting the rise in global temperature well below 2°C above pre-industrial levels, was ratified by more than 190 countries, and it represents, to a large extent, an agreement to meaningful action concerning the transformation and gradual decarbonization of the global energy sector, by implementing clean, low-carbon sources of energy, in order to mitigate climate change.

Changes in this direction have been underway for some time already. Reported energy intensity improvements across the global economy (1,8% in 2016) were due to important gains in energy efficiency and expansion of renewable energy sources worldwide, and have contributed to the fact that CO2 emissions related to the energy sector have not been growing anymore as of 2015 [22]. Falling fossil fuels prices, accompanied by a reform process concerning the fossil fuels subsidies in several countries, triggered significant reductions in such subsidies (from almost 500 Billion USD in 2014 to 325 Billion USD in 2015) [22]. From the roughly 1,8 Trillion USD invested annually in the global energy sector, the fraction allocated to clean energy has been growing steadily, at the same time with sharply declining investments in oil and gas deployments.

There are several challenges, trade-offs, and competing priorities that need to be resolved in the energy sector, but overall, there is agreement that clean energy technologies are capable of supporting the world to meet its energy demands while reducing the aforementioned environmental issues.

Solar Photovoltaic (PV) technology has been one of the fastest growing clean energy industries in the last decade. Since 2010, the world has added more solar PV capacity than in the previous four decades. In 2013 PV Systems were installed at a rate of 100 MW /day [22], the global installed PV capacity surpassed 150 GW in early 2014, then it reached 300 GW at the end of 2016, and is expected to reach 4.500 GW by 2050 [10]. The prices for PV Systems have declined by 66% over six years, for most markets, whereas PV Module prices have dropped by 80%. The costs of electricity from new systems vary between 90 USD/MWh and 300 USD/MWh, based on solar resource, PV System type, size, cost of overall system, market maturity and cost of capital [23]. IEA envisions that the PV's generation will reach 16% of the global electricity supply by 2050, and as the markets for renewable energy continue to develop, the costs of electricity from PV will become more uniform across the world, declining on average by 25% (as of 2020), by 45% (as of 2030) and by 65% (as of 2050), resulting in a range of 40 USD/MWh to 160 USD/MWh, at an 8% cost of capital [23].

To reach the 4.500 GW PV installed capacity by 2050, the annual rate of increase would need to be on average 124 GW, then growing up to 200 GW per year between 2025 and 2040. Solar park systems and rooftop systems will each have roughly half of the global market [23].

The geography of new PV deployments has also been changing dramatically over the last few years, resulting in a shift in the major global PV players. Whereas Europe has been leading the deployment of PV Systems for many years, most of the growth in PV installed capacity since 2015 has been in the Latin America and the Caribbean (14,5% growth rate), and Asia (12,4% growth rate). North America grew by 6,3% in 2015, and Europe only by 5,2% [10]. China alone added 15 GW installed PV in 2015 and Japan added 10 GW. As of 2016, the major PV electricity producers are: China (43 GW), Germany (40 GW), Japan (33 GW) and the United States (25 GW). By 2050 the expected deployment rates for the PV leaders are: China (1.731 GW), India (600 GW), the United States (600 GW), Japan (350 GW) and Germany (110 GW) [10].

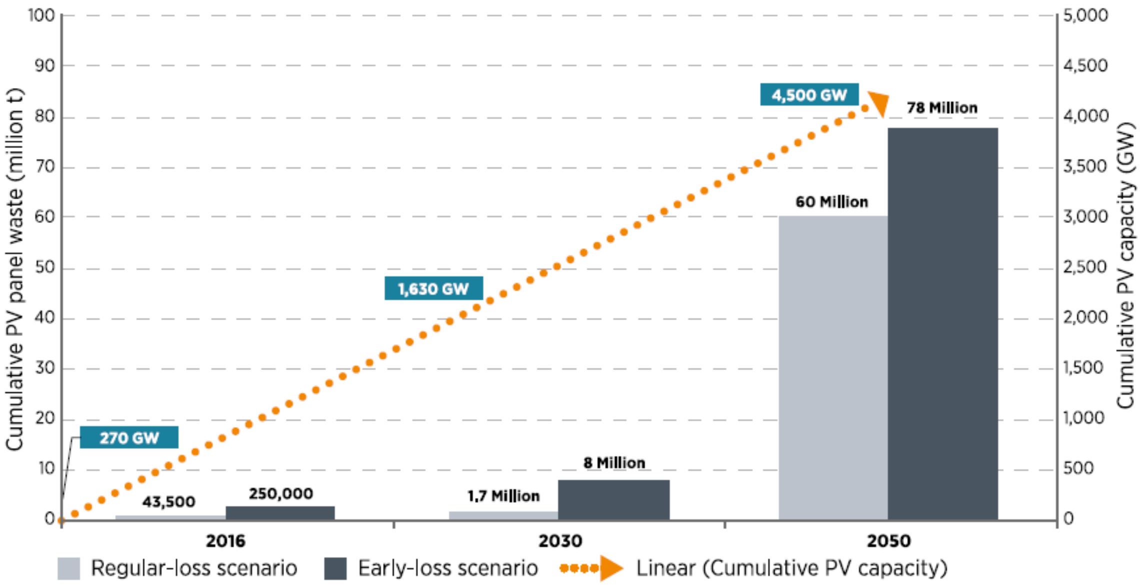

Figure 1 Overview Of Global PV Panel Waste Projections, 2016-2050[1]

As the global PV markets have been growing steadily, and assuming an average PV Panel lifetime of 30 years, it is evident that the volume of PV Panels reaching their end-of-life phase will also start to increase swiftly within the next few years, and will continue to upsurge over the next decades (see **Figure 1** for a quick overview, and **Figure 11** further down for a

[1] From IRENA, IEA PVPS 2016, [10]

detailed biennial projection). It was expected that the global cumulative PV Waste would reach between 44.000 Ton and 250.000 Ton by the end of 2016. By 2030 total PV Waste amounts are projected between 1.700.000 Ton and 8.000.000 Ton, and by 2050 between 60.000.000 Ton and 78.000.000 Ton **[10]**. The large margin between any of these pairs of figures is due to estimations by two different scenarios: Early Loss and Regular Loss of PV Panels. The large amounts of PV Waste generated annually by 2050 (5,5 – 6 Million Ton/year) are estimated to almost match the mass by weight to be included in that year's foreseen new installations (6,7 Million Ton).

The amplifying production and installation of PV Systems globally will definitely start to create pressure on resources' availability. On the other hand, the quickly growing amounts of PV Panel Waste will trigger important environmental challenges, due to their expected volume, and also due to their chemical composition, which includes certain hazardous elements. Based on **[10]**, currently only the European Union (EU) has started to implement specific PV (electronic) waste regulations, whereas most other countries would only classify PV Waste as general, or industrial waste, with just a few cases where testing for hazardous material content, prohibition of specific shipment, and disposal pathways are foreseen.

This groundbreaking report by IRENA and IEA (2016, **[10]**) found that PV Recycling activities could recover significant quantities of raw materials and other valuable components. If reintroduced into the economy flows, these could support the manufacturing process for new PV Panels, or could be traded globally on commodity markets, thus, contributing to the security of raw materials supply, unlocking important economic value, and generating employment opportunities in both the public and private sectors. Initial estimates indicate that raw materials technically recoverable from end-of-life PV Panels could cumulatively earn up to 450 Million USD by 2030, and could exceed 15 Billion USD by 2050, which is equivalent to producing 2 Billion new PV Panels, or 630 GW additional solar power capacity.

This thesis considers that a Systems Thinking, integrative approach to sustainably manage the end-of-life phase of PV Panels, and the adoption of the Reduce-Repair-Recycle paradigm, will be both instrumental for spawning profitable business ventures in emerging industries, such as PV Recycling, and will contribute to several of the 17 UN Sustainable Development Goals. These are the approaches which will certainly benefit our world, which is increasingly relying on renewable energy sources, during its transition towards a future with decarbonized energy systems.

In order to unlock the economic value expected from these new ventures while focusing on environmental sustainability of the PV end-of-life management, important institutional and policy action groundwork must be done across the world, in a timely manner, in order to be ready for the expected growth in PV Panel Waste. Incorporation of the Industry 4.0 paradigm will fortify and accelerate the world's transition towards a new, circular economy, fostering resource use efficiency and increased productivity.

The goal of this thesis is twofold: (1) present the current status of the PV technologies, future technology trends, global PV electricity production, and the expected streams of PV Panel Waste, and (2) identify and discuss concrete options to manage the PV end-of-life (and in fact the overall life cycle) in a sustainable manner, ensuring that these new business activities will contribute to achieving the UN Sustainable Development Goals by generating economic growth, creating new job opportunities, and safeguarding the environment. A linear programming model has been developed to, potentially, assist an environmental agency to optimally decide on the allocation of PV Panel Waste amounts, in a manner that minimizes the environmental costs due to transport and logistics related to PV end-of-life management.

2 General Methodology

The resources used for elaborating this thesis include: PV industry related books, books related to Industry 4.0 topics (IoT, Blockchain, Predictive Analytics, Linear Optimization Models, etc.), papers published in scientific journals, industry reports related to the development of photovoltaics, as well as current photovoltaics practices and statistics (e.g. First Solar, PV Cycle, etc.), reports by organizations like IEA PVPS and IRENA, website articles by authoritative sources (e.g. GreenBiz, Energy Transition-The Global EnergieWende, IBM, etc.), websites of international organizations and governmental entities (e.g., European Union, European Commission, Eurostat, etc.), all accurately referenced under the Bibliography section.

The starting point of this thesis lies with a 2016 pioneering report authored by IEA PVPS and IRENA (**[10]**), which has thoroughly analyzed, for the first time, the expected PV Panel Waste streams at global level, as well as current international practices in countries which have started, to a certain extent, to deal with the PV end-of-life phase.

The author’s professional background is Ecology and Conservation Biology, and System Engineering for the Information Technology industry. This is one reason why, based on direct professional knowledge, the author has focused particularly on environmental sustainability, and has also proposed and discussed as practical options to foster a sustainable PV end-of-life management a set of current, revolutionary concepts related to Industry 4.0 (predictive analytics, big data, IoT, blockchain, etc.), among other options.

The practical working approach for this thesis was simple: (1) read comprehensively about PV technologies, their global development, their current recycling processes; (2) read comprehensively about the UN’s Sustainable Development Goals (complemented with participation at formal events such as: Vienna Energy Forum, May 2017, BRIDGE for Cities, Sept. 2017) and identify synergies; (3) attempt to formulate the ideas and the entire work from a systems thinking perspective, building up a convincing case that there are concrete ways, cross-cutting various activity sectors, to achieve sustainability goals.

A certain effort has been spent to gain more knowledge and practical experience with linear optimization models. The methodology for the Linear Optimization Case Study about environmentally sustainable PV Recycling process is described with full details under the respective section.

Short interviews and discussions have been conducted on sustainability, PV industry, and Industry 4.0 topics, during the two events mentioned above, with the following panelists, to whom I am grateful for the given time and provided information (alphabetical order):

- Barbara Kreissler, Director of Professional Lighting, Department of Public and Government Affairs, Philips Lighting;
- Isabella Groegor-Cechowicz, Global General Manager, Public Services, SAP SE;
- Mafalda Duarte, Manager, Climate Investment Funds (World Bank);
- Okan Geray, Co-Rapporteur, International Telecommunication Union Study Group 20 Question 7, Smart Dubai Office;
- Peng Zheng, Project Manager, Foreign Economic Cooperation Office, Ministry of Environmental Protection, China;
- Peter Pluschke, Deputy-Mayor of Nürnberg, Germany;
- Philippe Scholtès, Managing Director, Programme Development and Technical Cooperation, United Nations Industrial Development Organization (UNIDO);
- Tania H. Rödiger-Vorwerk, Deputy Director General Directorate 31 – Federal Ministry of Economic Cooperation and Development (BMZ), Germany;
- Tareq Emtairah, Director, Department of Energy, United Nations Industrial Development Organization (UNIDO);

3 Photovoltaic Technologies Review

In order to develop sustainable approaches for the PV end-of-life management, it is important that PV recycling technologies are continuously aligned with research and development advances, as well as manufacturing trends and development of future PV technologies. This section is based on comprehensive literature analysis and provides a technological overview of the various PV technologies available on the market, and which will contribute to the anticipated large streams of PV Panel Waste over the next years and decades. As PV Panel manufacturing processes use a range of materials, with different levels of hazardous substances, reviewing the composition of PV Panels is an important aspect when defining regulations, and implementing optimal PV waste treatment processes and disposal pathways.

Table 1 below displays a quick listing of available PV technologies and their market share % for the 2014 to 2030 time period. **Table 2** further down compiles a list of the most important PV technologies and their highest efficiencies achieved so far under global AM1.5 spectrum (1000 W/m^2) at 25°C (adapted from [21]).

Table 1 Market share of PV panels by technology groups (2014-2030)[2]

Technology		2014	2020	2030
Silicon-based (c-Si)	Monocrystalline	92,0%	73,3%	44,8%
	Poly- or multicrystalline			
	Ribbon			
	a-Si (amorph/micromorph)			
Thin-film based	Copper indium gallium (di)selenide (CIGS)	2,0%	5,2%	6,4%
	Cadmium telluride (CdTe)	5,0%	5,2%	4,7%
Other	Concentrating solar PV (CPV)	1,0%	1,2%	0,6%
	Organic PV/dye-sensitised cells (OPV)		5,8%	8,7%
	Crystalline silicon (advanced c-Si)		8,7%	25,6%
	CIGS alternatives, heavy metals (e.g. perovskite), advanced III-V		0,6%	9,3%

Table 2 Terrestrial Cell and Submodule Efficiencies[3]

PV Technology	Efficiency (%)	J_{sc} (mA/cm^2)	V_{oc} (V)	FF (%)
Silicon				
Si (crystalline)	25.6 ± 0.5	41.80	0.740	82.7
Si (multicrystalline)	21.25 ± 0.4	39.80	0.667	80.0
Si (thin transfer submodule)	21.2 ± 0.4	38.50	0.687	80.3
Si (thin film minimodule)	10.5 ± 0.3	29.70	0.492	72.1
III-V cells				
GaAs (thin film)	28.8 ± 0.9	29.68	1.122	86.5
GaAs (multicrystalline)	18.4 ± 0.5	23.20	0.994	79.7
InP (crystalline)	22.1 ± 0.7	29.50	0.878	85.4
Thin film chalcogenide				
CIGS (cell)	21.0 ± 0.6	35.70	0.757	77.6
CIGS (minimodule)	18.7 ± 0.6	35.29	0.701	75.6
CdTe (cell)	21.0 ± 0.4	30.25	0.876	79.4
Amorphous/microcrystalline Si				
Si (amorphous)	10.2 ± 0.3	16.36	0.896	69.8
Si (microcrystalline)	11.8 ± 0.3	29.39	0.548	73.1
Dye sensitized				
Dye	11.9 ± 0.4	22.47	0.744	71.2
Dye (minimodule)	10.7 ± 0.4	20.19	0.754	69.9
Dye (submodule)	8.8 ± 0.3	18.42	0.697	68.7
Organic				
Organic thin film	11.0 ± 0.3	19.40	0.793	71.4
Organic (minimodule)	9.7 ± 0.3	16.47	0.806	73.2
Perovskite				
Perovskite thin film	15.6 ± 0.6	19.29	1.074	75.1
Multijunction				
Five junction cell (bonded)	38.8 ± 1.2	Sep.56	4.767	85.2
InGaP/GaAs/InGaAs	37.9 ± 1.2	14.27	3.065	86.7
GaInP/Si (mech. stack)	29.8 ± 1.5	14.10/22.70	1.46/0.68	87.9/76.2
a-Si/nc-Si/nc-Si (thin film)	13.6 ± 0.4	Sep.92	1.901	72.1
a-Si/nc-Si (thin film cell)	12.7 ± 0.4	13.45	1.342	70.2

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[2] From [10], Based on Fraunhofer Institute for Solar Energy Systems (ISE) (2014), Lux Research (2013)

[3] Measured @ 25°C, under Global AM1.5 Spectrum (1000 W/m^2). From Mallick, T.K., Sundaram, S., and Benson, D. (2016): “Solar Photovoltaic Technology Production”. FF = fill factor; J_{SC} = short circuit current density; V_{OC} = open circuit voltage

The Solar PV technologies have been typically categorized into three broad classes: (a) first generation solar cells, (b) second generation solar cells, and (c) third generation solar cells [21], described in more detail further down.

3.1 First Generation Solar Cells

The first generation solar cells represent the oldest PV technology.

They focus mainly on crystalline silicon (c-Si) technology (mono, poly and multicrystalline wafer technology), currently dominate the global market at approx. 92% market share, and represent ≥ 94% of the overall cell production in IEA PVPS countries.

Multicrystalline and monocrystalline silicon panels have 55% and respectively 45% share of the c-Si technology [10]. Monocrystalline silicon PV cells are based on wafers manufactured using a single crystal growth method and have commercial efficiencies between 16% and 25%. Multicrystalline silicon cells are based on multicrystalline wafers which are manufactured from a cast solidification process. Although they have lower conversion efficiencies (on average 14-18%), have remained popular because they are less expensive [20].

Silicon is the second most abundant element in the Earth's crust (about 28% by mass) after oxygen, and it has band gap of 1.1 eV, suitable for harnessing solar energy. The silicon purity determines the solar technology efficiency and performance stability. Average conversion efficiencies of 16–18% for standard size modules and very good performance stability (more than 25 years) are two important attributes for solar cell technologies to succeed commercially.

Monocrystalline silicon PV cells are the most common and oldest technology, and they consist of silicon atoms found in predetermined, fixed positions, forming a highly ordered microscopic lattice. The monocrystalline silicon wafers are produced under slow and carefully controlled conditions, which makes them some of the most expensive solar cells at a high conversion efficiency of 25%. The monocrystalline solar cell systems have a lower Balance of System (BoS) cost, and have 4–8% higher power output compared to other silicon-based solar cells, for similar module size. Monocrystalline systems are manufactured mainly by Taiwan PV companies and are on demand for rooftop applications in Japan and United States due to their superior energy output per construction area. In these countries, total installation was about 10 GW in 2014 and expected to rise in the coming years. A significant challenge for them comes from the multicrystalline solar cells marketing sector, with a higher market share currently [21].

Monocrystalline silicon solar cells are manufactured in different architectures to improve efficiency and stability. The common manufacturing method starts with a solar-grade silicon wafer, usually 300 µm thick (see **Figure 2**). The cleaning, or damage removal, is critical in silicon solar cell growth, in order to avoid recombination issues. The wafers are coated with an antireflection coating (ARC). For the p-type c-Si substrate, an n-type top layer will act as emitter through thermal diffusion, whereas for the n-type c-Si substrate, a p-type top layer will be used. Edge isolation is performed, in order to create an electrical pathway, then a thin dielectric coating is applied at the front and the back of the wafers, to passivate surface defects **[21]**. To form the electric field, the front and back of the cell are contacted using grid-pattern printed silver and aluminum pastes. The aluminum diffuses into the silicon and forms the back surface field through a thermal process (firing). Further layers are added to the wafer and laser structuring and contacting are employed in order to optimize the cell efficiency **[28]**.

Due to cost effective manufacturing methods, the PV industry started to manufacture in the 1980s polycrystalline silicon solar cells using silicon waste generated by the electronics industry. The conversion efficiency for polysilicon solar cells was low (≈ 13% for 2 cm^2 cells, under lab conditions) and thus, it was failing to attract investors for this technology. It has also triggered efforts to research alternative materials and processes to replace c-Si solar cells. In the 1990s however, the polycrystalline silicon solar cells conversion efficiencies improved significantly (35% under lab conditions, for 5 mm^2 areas), and became more attractive for investors **[21]**.

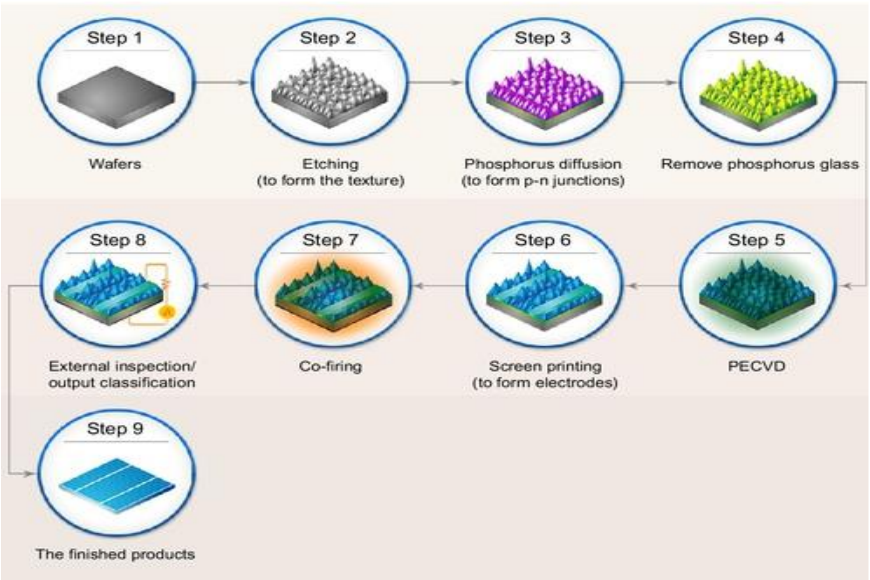

Figure 2 Standard Solar Cell Production Process For Silicon Based Solar Cells (from [21])[4]

[4] Mallick, T.K., Sundaram, S., and Benson, D. (2016): “Solar Photovoltaic Technology Production”

3.2 Second Generation Solar Cells

The goal for second generation solar cells was to reduce resource utilization and to explore new and cheaper materials, in order to generate lower-cost electricity. III-V compound semiconductor PV cells are formed using materials such as GaAs (Gallium Arsenide) on Ge (Germanium) substrates and have conversion efficiencies in excess of 40%. Due to high costs, they are typically used in concentrator PV (CPV) installations with tracking systems, or for space applications.

Thin film cells are formed by depositing very thin layers of direct band gap semiconductor materials with high absorption, such as CdTe (Cadmium Telluride), CIGS/CIS (Copper-Indium-Gallium-Diselenide) and amorphous silicon (a-Si), onto a backing material consisting of copper/aluminum, copper/graphite, graphite doped with copper, or polymer foil ([10], [20]). The manufacturing of amorphous Silicon (a-Si) products has been discontinued in the last years, due to low conversion efficiencies [10]. CIGS and CdTe PV cells are effective alternatives to c-Si PV and they are recognized for their stability and higher efficiency: they have reached world record efficiencies of 22.3% (CIGS) and 22.1% (CdTe), for small area cells ([20], [21]).

Silicon-wafer technology had difficulties in achieving PV module production costs under 1 EUR/W, which has been considered essential for cost-competitive electricity generation. China, however, benefited from its very large production capacity of c-Si modules, cheap labour and perhaps also other factors, and it managed to bring the manufacturing costs down to 0,5 EUR/W. The European market could not compete with these prices and it almost collapsed, unsettling the PV market. This stirred global controversies over module pricing, which led to legal actions against the Chinese manufacturers, and sent a direct message to thin film PV manufacturers to improve module conversion efficiencies beyond 14%, in order to remain on the PV market [21].

Thin film PV technologies are considered more suitable for building integrated applications and could become an effective alternative to silicon technologies by improving the deposition process of high quality materials and fine-tuning the manufacturing parameters. Once these methods have been optimized, they could provide production costs lower by at least one order of magnitude. Other advantages of thin film technologies are:

- Their combination of rigid and flexible substrates render them suitable for space applications, building integrated photovoltaics (BIPV) and adjustable electronics;
- Considerable material savings, due to the fact that much thinner semiconductor layers (e.g., typically 3 μm currently, with potential to be reduced to 1–2 μm in the future) are needed to harness more than 90% of the incident solar light, at an optical absorption coefficient of ~ 10^5 cm^{-1}, i.e. approx. 100 times higher than c-Si;

- Lower energy payback time than c-Si PV with estimates suggesting that improved CdTe PV has the lowest payback time among all PV technologies, and it could be as low as 6 months;
- Less absorption losses and enhanced collection due to better heterojunction formation and device engineering;
- Easy manufacturing such as roll-to-roll (R2R) process, and stacking of devices as tandem and multijunction devices could cover the full solar spectrum and could drive theoretical efficiencies up to 67%, **[21]**.

For CIGS modules, the junction needed for the photovoltaic effect is formed through thin layers of cadmium sulfide. Zinc oxide or other conducting oxides are used as a transparent front contact. Solar glass is typically used for the encapsulation and front glass layers, providing protection from long-term oxidation and from degradation due to water intrusion. Cadmium-sulfide, but also other cadmium-free materials, e.g., zinc, zinc oxide, zinc selenide, zinc-indium-selenide, could be used as a buffer layer. CIGC panels contain also cell absorbers made of chalcopyrite. There is some research currently investigating the substitution of aluminum for indium, or silver for copper **[24]**.

CdTe modules can be grown in substrate, or in superstrate configurations, with the latter option preferred for better efficiencies. The transparent conductive oxide, intermediate cadmium sulphide (CdS) and the CdTe layers are deposited on a glass superstrate. The back layer is formed with copper/aluminum, copper/graphite, graphite doped with copper, and an encapsulation layer laminates the back glass to the cell **[10]**.

CdTe modules are very attractive due to their chemical simplicity and the robust stability. It has been demonstrated that this technology is very stable for terrestrial applications, and it's also superior to Si, GaAs, CIGS for space applications, under high energy-photon and electron irradiation conditions **[21]**.

Figure 3 compares the material composition of the main PV panel technologies between 2014 and 2030 (expected evolution). A typical crystalline PV Panel with 60 PV cells on aluminum frame has a 270 watt-peak (Wp) capacity and weighs 18,6 kg (**[10]** based on Trina Solar reports), whereas a standard CdTe panel, 110 Wp is expected to weigh on average 12 kg (**[10]** based on First Solar reports), and a CIGS panel is typically at 160 Wp and 20 kg ((**[10]** based on Solar Frontier reports).

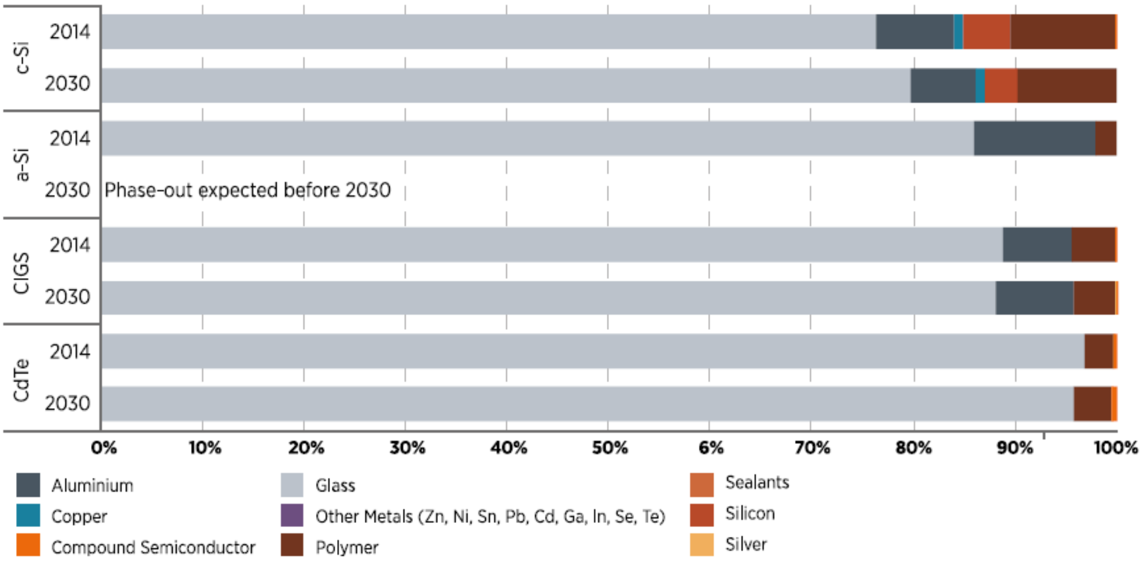

Figure 3 PV Panel Material Composition as % Of Total Panel Mass - 2030 Trends (from [10])[5]

The current composition for most common c-Si PV Panels consists of 76% glass (the panel cover surface), 8% aluminum (the frame), 10% EVA encapsulant (the copolymer of ethylene and vinyl acetate), 5% silicon (the solar cells), 1% copper (interconnectors), less than 0,1% silver (contact lines) plus other metals e.g., tin, lead).

CIGS PV Panels consist of 89% glass, 7% aluminum, 4% polymer content and less than 1% other metals (out of which 10% copper, 28% indium, 10% gallium, 52% selenium), whereas CdTe PV Panels are made of 97% glass, 3% polymer, ([24], [25], [26], [27]).

3.3 Third Generation Solar Cells

The third generation solar cells, such as Dye Sensitized Solar Cell (DSSC), organic solar cells (OPV), and nanostructured solar cells, are aimed at reducing manufacturing costs and using environment-friendly materials. During recent years, solar cells based on perovskite (a Calcium Titanium oxide mineral composed of Calcium Titanate, $CaTiO3$) have reached promising efficiencies, in excess of 20% under lab conditions, but have not yet become effective commercial products [20].

DSSCs have been extensively studied during the last couple of decades, as industry and academic research have worked towards improving their efficiencies. This technology follows a different approach of bulk-heterojunction (BHJ) formation in the nanometer length regime. It consists of nano-composites of mesoporous titanium dioxide and inorganic dyes (typically ruthenium complexes). The working principle is by excitonic electron-hole pair generation upon excitation by light and dissociation, leading to a charge separation at the

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[5] From IRENA, IEA PVPS 2016 ([10]), based on Bekkelund ([24]) and others

nano-interface. The absorption of photons and electron transport take place through dyes and the n-type nanocrystalline titanium dioxide. The holes are transported through a hole-transporting material (HTM), which could be a redox liquid electrolyte, a ion conducting polymeric electrolyte (quasi-solid state), or a hole conducting conjugated polymer material. There have been promising results under lab conditions concerning the efficiency, however, the liquid junction seems to have hit a plateau currently, which, among other issues (e.g., a lack of sensitizer dyes with wider spectral coverage, atmospheric degradation, and engineering issues such as encapsulation and sealing off the liquid junction device), has prevented the technology to take off commercially **[21]**. The global DSSC market value was estimated at 49,6 Million USD in 2014, and this PV technology, with very good performance under diffused light conditions, announces to be one of the best candidates for achieving the zero emissions buildings sustainable goal, by integrating renewable energy sources with modern building concepts. As building integrated photovoltaics (BIPV), and building applied photovoltaics (BAPV) applications will be increasingly deployed, it is expected that the market for DSSC technology will grow more than 12% from 2015 up until 2022 **[21]**.

A typical organic solar cell (OPV) consists of one or several photoactive materials sandwiched between two electrodes. In a bilayer device, light is absorbed in the photoactive layers composed of donor and acceptor semiconducting organic materials, triggering the photoelectric effect. The donor substrate donates electrons and mainly transports holes, whereas the acceptor substrate attracts and transports the electrons. Due to the concentration gradient, the excitons diffuse to the donor/acceptor interface (exciton diffusion) and separate into free holes (positive charge carriers) and electrons (negative charge carriers). An electric current is generated when the holes and electrons move to the corresponding electrodes. Important advantages of OPV technology compared to other products are: can be deployed in large areas and in flexible solar modules; can have reduced manufacturing cost compared to silicon based products; undergo a relatively simple manufacturing process. In order to catch up on the performance side however, the donor and acceptor OPV substrates require good extinction coefficients, high stabilities, good film morphologies, and great hole/electron mobility, in order to maximize the charges' transport. Additionally, the donor substrate, which is responsible to absorb the light flux, must have broad optical absorption characteristics, matching the solar spectrum. Designing various OPV architectures (e.g., bulk-hetero-junction, inverted device structures), complemented with the development of low band gap conjugated polymers and innovative organic small molecules as donor materials, are factors which have contributed to significant OVP performance improvements. It is estimated that the OPV market will grow to 87 Million USD by 2023 **[21]**.

3.4 Future Trends For PV Panel Material Composition

PV research and industry trends suggest that new technologies will gradually follow on the markets, focusing on thinner and more flexible wafers (resulting in significant material savings), more complex cell structures, with improved conversion efficiencies, as well as diversified back-contacts, e.g., in the form of hetero-junctions.

Reductions in material usage and substitutions are being researched particularly for hazardous elements, e.g., lead, cadmium, selenium, but also for common materials which are not considered harmful: glass, polymer, aluminum, silver and lead for c-Si panels; glass, polymer, aluminum, gallium, indium for CIGS panels; glass, polymer, nickel and others for CdTe panels **[10]**.

The glass content of c-Si PV Panels is expected to increase to 80% of total panel's weight by 2030 (see **Figure 3**), the silicon and aluminum contents will decrease to 3% and respectively 7%. Also, the content of other metals will decrease slightly by that time. The glass content of thin film technologies is expected to decrease by 2030, whereas the content of compound semiconductors and polymers will increase. For CIGS the aluminum content will rise by 1%, semiconductor content will increase by 0,2% and other metals will be slightly reduced, by 0,02%. For CdTe the glass content will go down to 96%, polymer mass will increase to 4%, semiconductor materials will decline by half, and there will be a slight increase in the share of other metals (e.g., nickel, zinc and tin) **[10]**.

The indium tin oxide from the front electrodes may be replaced with more abundant and cheaper elements, e.g., fluorine-doped tin oxide. The glass composition, thickness and reflective coating will be subjected to further optimizations. New studies are investigating the possibility to replace or reduce the amount of polymers used for encapsulants and backsheet foils, as these are currently not recycled. Two alternatives investigated currently are: use thermoplastics as encapsulants (are easier to separate before recycling) and eliminate encapsulants **[28]**.

Silver is the most expensive component per unit of c-Si PV Panel mass and currently, the PV industry consumes between 3,5% and 15% of total silver production in the world, with typical c-Si PV panels consisting of 6-10 gr silver. The silver content of solar cells, currently used for the screen-printed contact lines on the cell front area in about 95% of solar cells, is expected to decrease significantly by 2018, based on recent advances in inkjet and screen-printing technologies. Furthermore, a 99% reduction in silver usage could be achieved by new metallization methods based on ink jetting seed layers then plated with nickel and copper **[28]**.

Moreover, silicon content could be reduced significantly (up to 50%) by using thinner cells and a back-contact cell design, which would also reduce energy consumption by 30% **[28]**.

In terms of conversion efficiencies, the CIGS technology is expected to become at least 20% by 2030, whereas CdTe technologies are targeting 25% for lab conditions and at least 20% for commercial applications, already by 2020.

3.5 PV Panel Waste Classification

The classification of PV Panel Waste is an essential step in order to identify and quantify the risks potentially posed to the environment and/or human health by the end-of-life management of PV Panels. Depending on jurisdiction, such classification typically follows the general waste classification principles (particularly e-waste), i.e., by considering the PV Panel Waste material composition, by mass or volume, and accounting for physical and chemical properties of the used materials, such as: soluble, flammable, oxidizing, irritant, aspiration (inhalation) toxicity, carcinogenic, corrosive, Eco toxic, persistent organic pollutants, etc. The goal is to formally define and then implement the appropriate treatment (recycling) and eventual disposal pathways for PV Waste, in order to minimize the risks and threats, and ultimately to contribute to a sustainable end-of-life management of PV Panels.

For example, one significant risk is that materials used in the PV Panels will leach out into the environment, therefore it is necessary to assess this risk, determine and implement suitable containment measures (general waste management knowledge).

Waste can be classified into various categories (hazardous, non-hazardous, etc.) and sub-categories (industrial, domestic, e-waste, construction, mixed-solid, municipal, etc.), depending on national and international regulations, such as the Basel Convention on the Control of Transboundary Movements of Hazardous Wastes and Their Disposal **[30]**, which is an international treaty designed to control the international movement of (hazardous) waste, and particularly its unethical transfer from developed towards less developed countries. Such classification then determines the allowed, as well the prohibited pathways for waste collection, transport, tracking and reporting, treatment and final disposal.

As of 2014, approx. 92% of the world's PV Panels were based on c-Si PV technology (see **Table 1**). More than 90% of their mass can be classified as non-hazardous waste, consisting of glass, aluminum and copolymer (see **Figure 3**), but there are also other components, in smaller amounts, which could be considered hazardous, e.g., silicon, silver, traces amounts of tin and lead, and which, depending on the applicable jurisdiction, would need to be subjected to specific recycling procedures and disposal. Similarly, the thin film PV Panels are composed of more than 98% glass, copolymer and aluminum (content % varies between CIGS and CdTe technologies), but there are also environmentally hazardous components, e.g., copper and zinc (potentially hazardous), indium, gallium, selenium, cadmium telluride, lead **[10]**.

Leaching tests represent widely used methods in the world currently, for the characterization of PV Panel Waste and **Table 3**, based on **[10]** and **[31]**, compares the details from the leaching tests implemented by three PV major player states currently.

Based on **[10]**, a liquid is being exposed to fragments from broken PV Panels for a certain period of time and in a specific liquid: solid ratio. Some of the materials contained by the PV Panel sample will dissolve and the leachate can be analyzed for mass concentration of hazardous materials. Different countries may observe different thresholds for the detected concentration of harmful components in order to decide if a certain waste is hazardous or non-hazardous. For example, US considers hazardous waste a PV Panel which results in ≥ 5 mg lead/liter leachate, whereas the Japan threshold is 0,3 mg lead/liter. Cadmium threshold is 1 mg/liter in US, 0.3 mg/Liter n Japan, and 0,1 mg/liter in Germany. Consequently, depending on the detected concentration, such PV Panels could be considered hazardous waste in some jurisdictions, but non-hazardous waste in other jurisdictions, and this aspect is particularly important especially in geographical and political regions where the PV Panel Waste could be transported from one jurisdiction to another, which has more relaxed criteria for classifying PV Waste as hazardous, and thus, impose more drastic measures for its treatment and disposal.

Table 3 PV Waste Characterization: Leaching Tests Used In US, Germany, Japan[6]

	United States	Germany	Japan
Leaching test	US Environment Protection Agency method 1311 (TCLP)	DIN EN German Institute for Standardization standard 12457-4:01-03	Ministry of Environment Notice 13/JIS K 0102:2013 method (JLT-13)
Sample size (centimetres)	1	1	0,5
Solvent	Sodium acetate/ acetic acid (pH 2.88 for alkaline waste; pH 4.93 for neutral to acidic waste)	Distilled water	Distilled water
Liquid:solid ratio for leaching test (e.g. amount of liquid used in relation to the solid material)	20:1	10:1	10:1
Treatment method	End-over-end agitation (30±2 rotations per minute)	End-over-end agitation (5 rotations per minute)	End-over-end agitation (200 rotations per minute)
Test temperature	23±2°C	20°C	20°C
Test duration	18±2 hr	24 hr	6 hr

[6] Based on **[10]** and **[31]** Sinha, P. and A. Wade (2015), "Assessment of Leaching Tests for Evaluating Potential Environmental Impacts of PV Module Field Breakage"

In most countries the PV Panel Waste still falls under the general waste classification [10], with the notable exception of EU countries, where PV Panel Waste classification and management are now regulated as e-waste by the recast WEEE Directive/2012/19 of the EU [32].

The WEEE Directive/2012/19 is a very important, comprehensive legal framework which provides common terminology for e-waste management across the EU, common coding of waste characteristics, decisions about waste recyclability. It fosters environmentally sustainable business practices, and aims at improving the recycling efficiencies from e-waste management activities, by setting specific targets ([10], [32]).

3.6 PV Panel Waste Projections

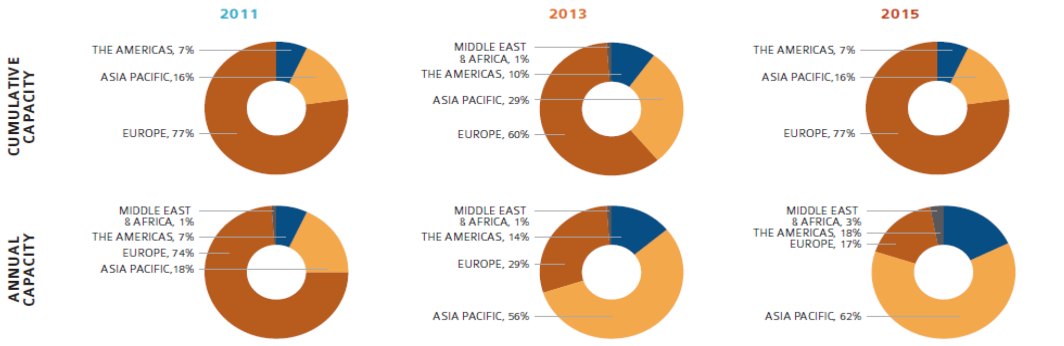
In order to build up the business case for the sustainable management of photovoltaics end-of-life, and particularly concerning the economic sustainability aspects, it is necessary to first analyze the PV markets evolution over the past two decades, consider the industry specific roadmap mid- and long-term, and then to develop various scenarios for the projections of cumulative PV Panel Waste amounts, by regions of the world, and by country, for short-, mid-, and long-term time periods.

3.7 Evolution Of Installed Solar Power Capacity

The information presented in this section is compiled following the author's analysis of recent flagship reports by IEA PVPS Programme and IRENA (e.g., Trends in Photovoltaic Applications 2016, Technology Roadmap – Solar Photovoltaic Energy 2014, IEA PVPS Annual Report 2016, World Energy Outlook 2016, 2016 - Snapshot Of Global Photovoltaic Markets).

Between 2003 and 2013, the cumulative PV installed capacity worldwide grew at an average rate of 49% annually. In 2013 the total global capacity exceeded 135 GW, as 37 GW of new capacity were installed in thirty countries, at a rate of 100 MW per day. Asia overtook Europe for the first time in installed PV capacity, China alone installed more than 11 GW, i.e., more than the whole Europe in 2013. Japan was second (≈ 7 GW) and and the US third (> 4 GW) [34].

Overall, during the last two decades, and up until the end of 2015, it has been estimated that more than 228 GW solar power capacity have been installed all over the world [20], see also Figure 4. By the end of 2015 about 196 GW PV installations, mostly grid-connected, had been installed in the IEA PVPS countries (the list of 31 member states of this Programme is available at http://www.iea-pvps.org/index.php?id=4,).



	CUMULATIVE CAPACITY (MW)					ANNUAL CAPACITY (MW)				
REGION	2011	2012	2013	2014	2015	2011	2012	2013	2014	2015
THE AMERICAS	4 575	8 277	13 566	20 960	29 906	2 225	3 702	5 289	7 394	8 946
ASIA PACIFIC	11 177	18 725	39 819	63 598	94 272	5 387	7 548	21 094	23 780	30 673
EUROPE	53 534	70 937	82 070	89 248	97 843	22 463	17 404	11 133	7 178	8 595
MIDDLE EAST & AFRICA	220	293	777	1 911	3 355	133	72	484	1 134	1 445
REST OF THE WORLD	371	633	917	1 363	2 360	145	262	284	447	996

Figure 4 Evolution Of Annual And Cumulative PV Capacity By Region 2011-2015 (from [20])[7]

China, a PVPS Programme participant, installed a record 15,15 GW PV capacity in 2015, occupying the first place (as in 2014 and 2013), and it overtook Germany (the top PV country before 2015), with a total installed capacity of 43,5 GW. The other 40 countries considered in the 2015 PV capacity cumulative figure are not part of the IEA PVPS Programme, and represented a cumulative 31 GW, with the following notable examples: UK (≈ 10 GW), Greece (2,6 GW), The Czech Republic (2,1 GW), Romania (1,3 GW). The highest cumulative installations at the end of 2015 were in India (≥ 5 GW), South Africa (0,9 GW), Taiwan (0,8 GW), Pakistan (≈ 0,78 MW), Chile (0,9 GW), Ukraine (0,6 GW) and Slovakia (0,5 GW).

Many other countries have started to develop PV capacity but most of them have not reached a significant deployment level, by the end of 2015 (50 countries had at least 100 MW cumulative at the end of 2015, and 114 countries had more than 10 MW) [20].

With ≈ 51 GW added PV capacity, the global market grew by ≈ 26,5% in 2015, a new record for the annually installed PV capacity. China (see above), Japan (10,8 GW installed in 2015), the US (7,3 GW), the UK (4,1 GW) and India (2,1 GW) are the top five countries in 2015, which represent 78% of added PV capacity in 2015, and 52% in terms of cumulative PV capacity. The former PV market leader, Germany, continued to decline in installed PV capacity: 1,9 GW in 2014, and 1,46 GW in 2015, well below the 2008 level.

In 2016 there have been approx. 75 GW added PV capacity worldwide, which means more than 50% of what was added in 2015, bringing the global PV capacity to approx. 300 GW (with at least 302 GW producing electricity at the end of the year [33]) (see **Figure 5**).

[7] IEA PVPS "Trends 2016 in Photovoltaic Applications"

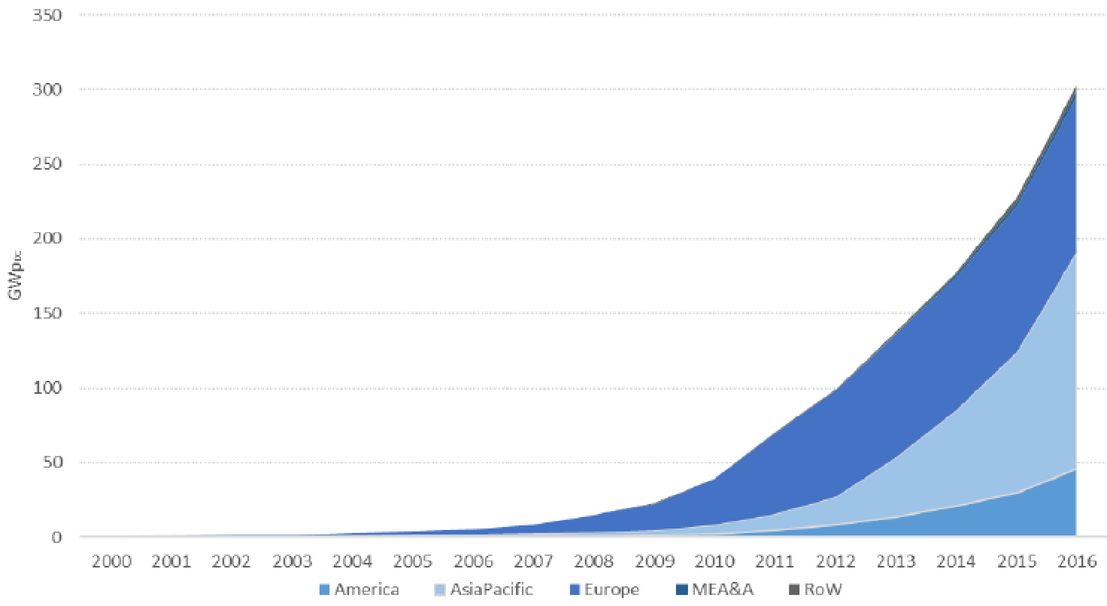


Figure 5 Global Cumulative Growth Of PV Capacity: 2000-2016 (from [64])

China, the US and Japan were again the top performers, accounting together for three quarters of the additional installed capacity in 2016, see **Figure 6**. In 2016, 24 countries passed the 1 GW mark, six countries exceeded 10 GW total PV capacity, four countries exceeded 40 GW, and China alone represented 78 GW, with Japan ranking second (42,8 GW), Germany ranking third (41,2 GW), and the USA ranking fourth (40,3 GW). With approx. 103 GW of total PV capacity, Europe lags significantly behind Asia **[64]**.

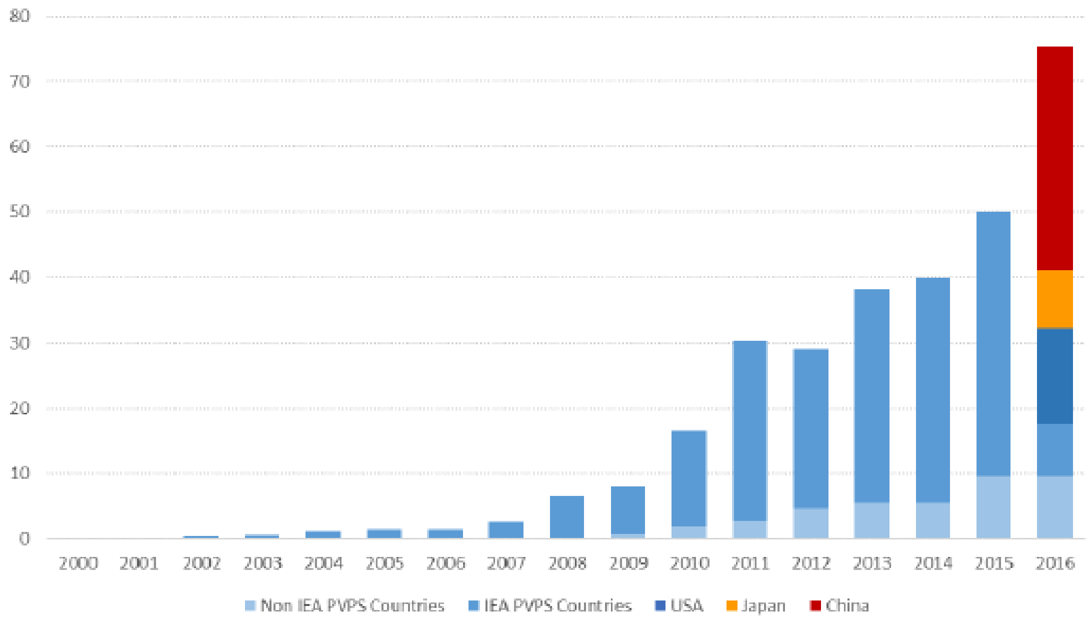


Figure 6 Annual PV Installed Capacity 2000 – 2016 (from [64])

IEA PVPS came up with projections for mid- and long-term globally deployed PV capacity by developing and updating annually a PV technology roadmap, and focusing on three scenarios: 6DS (the 6° Scenario, business as usual, projecting that global energy demand will increase by more than two thirds for 2011-2050), 2DS (the 2° Scenario, anticipating a radical transformation of the global energy systems in order to limit the increase in global average temperature to 2° C), hi-REN (the high renewables scenario aims at reaching the 2° target by faster and extended deployment of renewables). In order to achieve the goals of the hi-REN scenario, the 2014 solar PV roadmap increased considerably the PV capacity deployment, compared with the 2010 version: 1.700 GW by 2030 (from 870 GW) and 4.670 GW by 2050 (from 3.155 GW), see **Table 4**.

Table 4 Projected PV Capacities By Region For hi-REN Scenario 2030, 2050 (GW) (based on [34])

Year	US	Other OECD Americas	EU	Other OECD	China	India	Africa	Middle East	Other Developing Asia	Eastern Europe and Former USSR	Non-OECD Americas	World
2013	12,5	1,3	78	18	18	2,3	0,3	0,1	1,4	3	0,2	135
2030	246	29	192	157	634	142	85	94	93	12	38	1721
2050	599	62	229	292	1738	575	169	268	526	67	149	4674

The PV technology is envisioned to provide 16% of global electricity by 2050, with China as top player, with 35% of global PV electricity production. This is particularly relevant for subsequent projections of PV Panel Waste (further down).

As the PV markets have been developing, also PV investment costs have been falling significantly during the last years (see **Figure 7**), and an average cost reduction of 25% is expected by 2020, 45% by 2030, and 65% by 2050, leading to a 40-160 USD / MWh, assuming a 8% cost of capital. Moreover, the PV Systems performance ratios have improved, and it is expected that the majority of new PV capacity will be gradually installed in areas with great solar radiation, and consequently, the average PV LCOE is expected to decrease, and become more uniform worldwide. However, it is also largely considered that the era of decreasing prices for the PV cells may plateau soon, but there is still great potential for financial savings through economies of scale, improved efficiencies, and factors such as Carbon taxes. The RnD and manufacturers will be likely focusing on technological improvements, e.g., increasing conversion efficiencies and PV Systems lifetime, and also designing products with the end-of-life phase in mind (to improve recycling efficiencies, to replace rare, or hazardous materials with more sustainable elements) **[34]**.

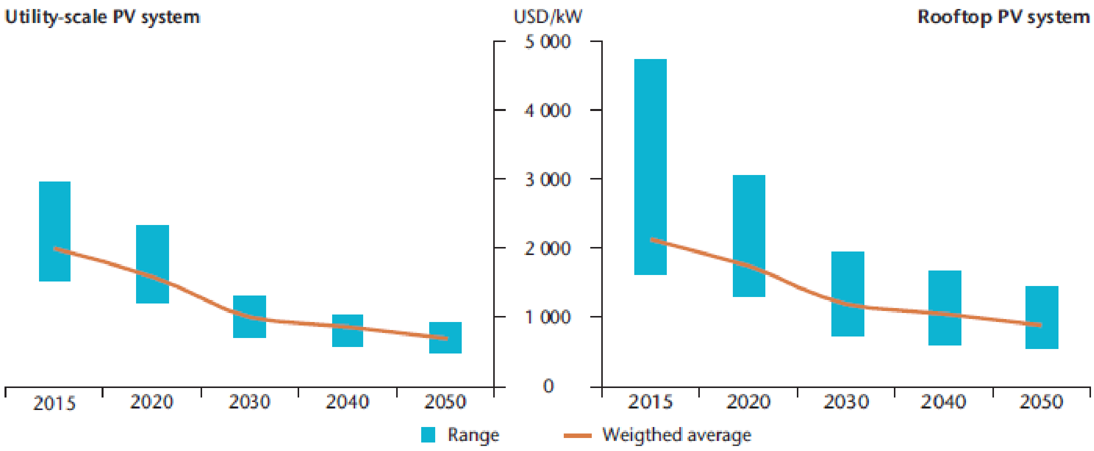


Figure 7 PV Investment Costs Projections For hi-REN Scenario (from [34])

3.8 Solar PV Panel Waste Projections

In order to start modelling, for the first time, the expected amounts of PV Panel Waste for the next decades, IEA PVPS and IRENA (2016) have initially developed annual estimates of the installed PV capacity, by interpolating the PV roadmap values for 2015, 2020 and 2030 **[10]**. The average annual installed PV capacity growth rate was calculated at 8,92% for each five-year period between 2015-2030, with the observation that this value may vary by regions/countries, depending on the respective political and economic landscapes. The annual projections were extended up until 2050, at a more moderate growth rate of 2,5% annually.

Two scenarios, Regular Loss and Early Loss, have been considered for the PV Panel Waste model. The PV Panel Waste sources are typically considered as follows: (1) manufacturing scrap, generated during panel production; (2) broken panels, during manipulation and transportation; (3) broken panels during installation and use; (4) the end-of-life phase. Two main factors have been calculated and used for modelling the PV Panel waste amounts: the PV Panel weight and the probability of PV Panel failure, or losses, across the whole lifetime.

The installed PV capacity was converted to mass figures (metric Tons) by using an average factor PV Panel Ton / MW Power which was determined by averaging a series of available data on panel weight and capacity, and including also a correction factor, accounting for changes in the PV Panel design, using gradually less material (see **Figure 8**).

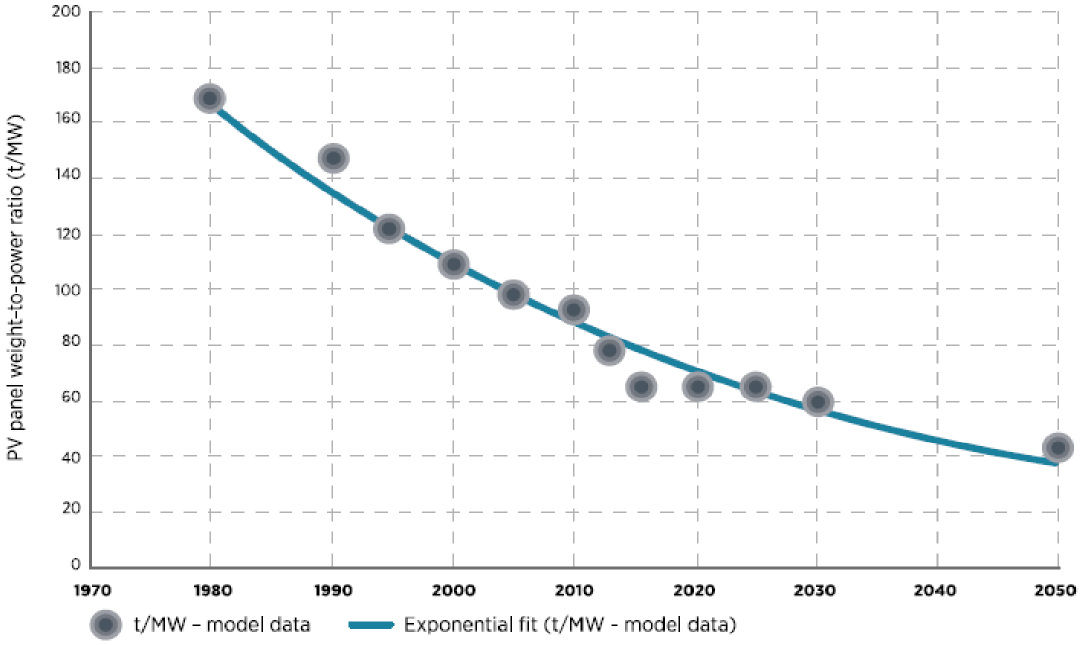


Figure 8 Projection Of PV Panel Weight-To-Power Ratio (Ton/MW) (from [10])

The probability of PV Panel losses was calculated by taking into account: (1) 'infant failures' (occurring on average two years, and up to four years, after installation), (2) 'midlife failures' (occurring from five to eleven years after installation), and (3) 'wear-out failures' (occurring between twelve years after installation and up until the PV Panel end-of-life assumed at 30 years for this model) **[10]**.

Figure 9 below displays the main causes and frequencies of PV Panel failures. Major infant failures are due to light-induced degradation, poor planning and inadequate installation work, issues with the electrical systems (e.g., junction boxes, string boxes, cabling, controllers). Midlife failures are mainly caused by the degradation of the anti-reflective glass coating, delamination, cracked cell isolation, EVA degradation. The wear-out failures add up to those reported as midlife failures issues with interconnectors as well as corrosion. It was also reported that PV cells manufactured after 2008 are more likely to experience microcracks, due to the fact that these cells are thinner. Natural causes, such as increased exposure to mechanical load from wind, snow loads, hail, and temperature changes, are also reported to impact all life phases of the PV Systems and add to the deterioration of cell interconnectors, glass cover, junction boxes, etc.

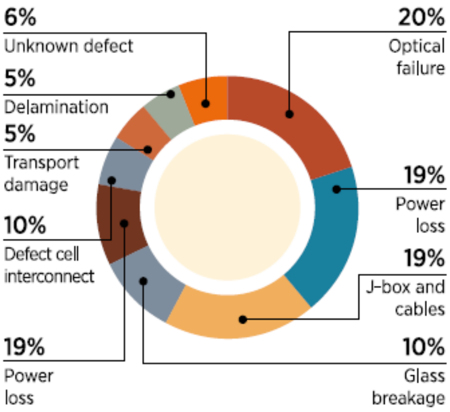


Figure 9 PV Panel Failures Rates Based On Customer Reports (from [10])

The PV Panel Waste scenarios were modelled with a Weibull function, which gives one of the most widely used distributions in reliability engineering and device life data analysis (e.g., to model a cumulative distribution of device failure rates).

$$F(t) = 1 - e^{-(\frac{t}{T})^{\alpha}} \quad (1)$$

Where:

t = time in years

T = average PV Panel lifetime

α = shape factor, controlling the shape of the Weibull distribution

The PV Panel Regular Loss methodology assumed 30-year average PV Panel lifetime (a common assumption derived from PV LCA analysis), 99,99% probability of loss 40 years after installation, when the PV Panels are dismantled and sent to recycling/disposal (value also taken from literature), and the shape factor, compiled based on values reported in literature for modelling PV Panel loss probabilities **[10]**.

The PV Panel Early Regular Loss methodology had the same assumptions as above, but with a slightly different approach for calculating the shape factor, by a regression analysis from existing values and incorporating information on early failures. Additionally, this scenario's model assumed 0,5% damages during transport and installation, 0,5% failures during the first two years after installation, 2% after ten years, and 4% after 15 years.

The obtained Weibull distributions are displayed, for both scenarios (different shape factors) in **Figure 10**. It is apparent that the choice of shape factors, based on Early-Loss and Regular-Loss, has an opposite effect on the failure rate distribution after 30 years lifetime in these scenarios.

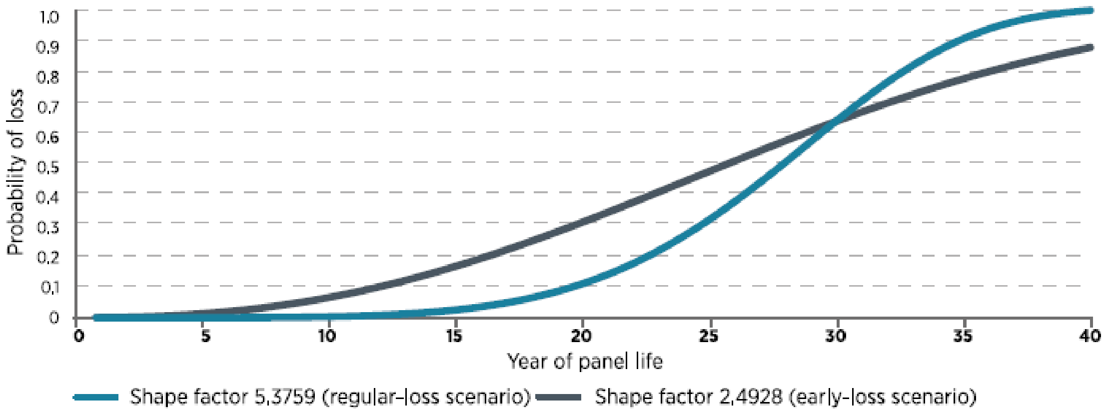


Figure 10 Weibull Probability Distribution For PV Panel Losses (from [10])

For both scenarios, the failure probability (α) was multiplied by the weight of new PV Panels installed annually, in order to generate the PV Panel Waste global cumulative projections up until 2050 (see **Figure 11)**, and also detailed per world region and per country (see **Table 5**).

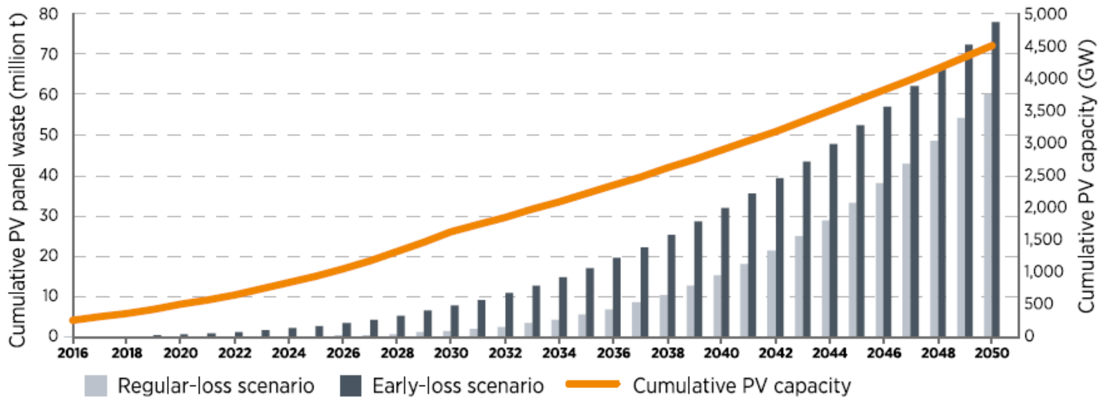


Figure 11 Global Cumulative PV Panel End-Of-Life Waste Projections (Million Ton) (from [10])

The results of this modelling effort suggest that global cumulative PV Panel waste would amount to 250.000 Ton by the end of 2016, according to the Early-Loss scenario, and this amount would represent only 0,6% from the total e-waste at that time. PV Panel Waste, however, will start to be generated at a faster pace during the next years and decades. Up until 2030 it is projected that PV Panel Waste will grow to 1,7 Million Ton, in the Regular-Loss scenario, and up to 60 Million Ton worldwide until 2050. The Early-Loss scenario projects even higher amounts of PV Waste: 8 Million Ton until 2030 and 78 Million Ton until 2050. As there were several assumptions and estimations considered in these models (the best known estimation efforts at the time of writing) there is important room for variation, e.g., some sources of PV Waste have not been accounted for (e.g., PV manufacturing scrap was omitted from these first-ever PV Waste models), therefore the IEA PVPS and IRENA experts currently consider that PV Panel Waste amounts would likely be situated between the values projected by the two scenarios **[10]**. This thesis observes there is a large margin of interpretation for these expected values, and it is apparent that such estimations would not be reliable enough for entities interested in starting a PV Recycling business, nor for governmental agencies tasked with the coordination of PV Waste collection, storage, and transport activities, etc.. This aspect, and the necessity to continuously fine-tune such PV Waste estimations through improved, comprehensive data collection and analysis, will be re-iterated in the main Discussion section, under the options to achieve an economically and environmentally sustainable PV end-of-life management.

The following **Figure 12** displays the foreseen trends (2020-2050) for the proportion between amounts (in Million Ton) of PV Panels reaching their end-of-life phase, and amounts of new installed PV mass, for the Early-Loss scenario (upper graphic) and Regular-Loss scenario.

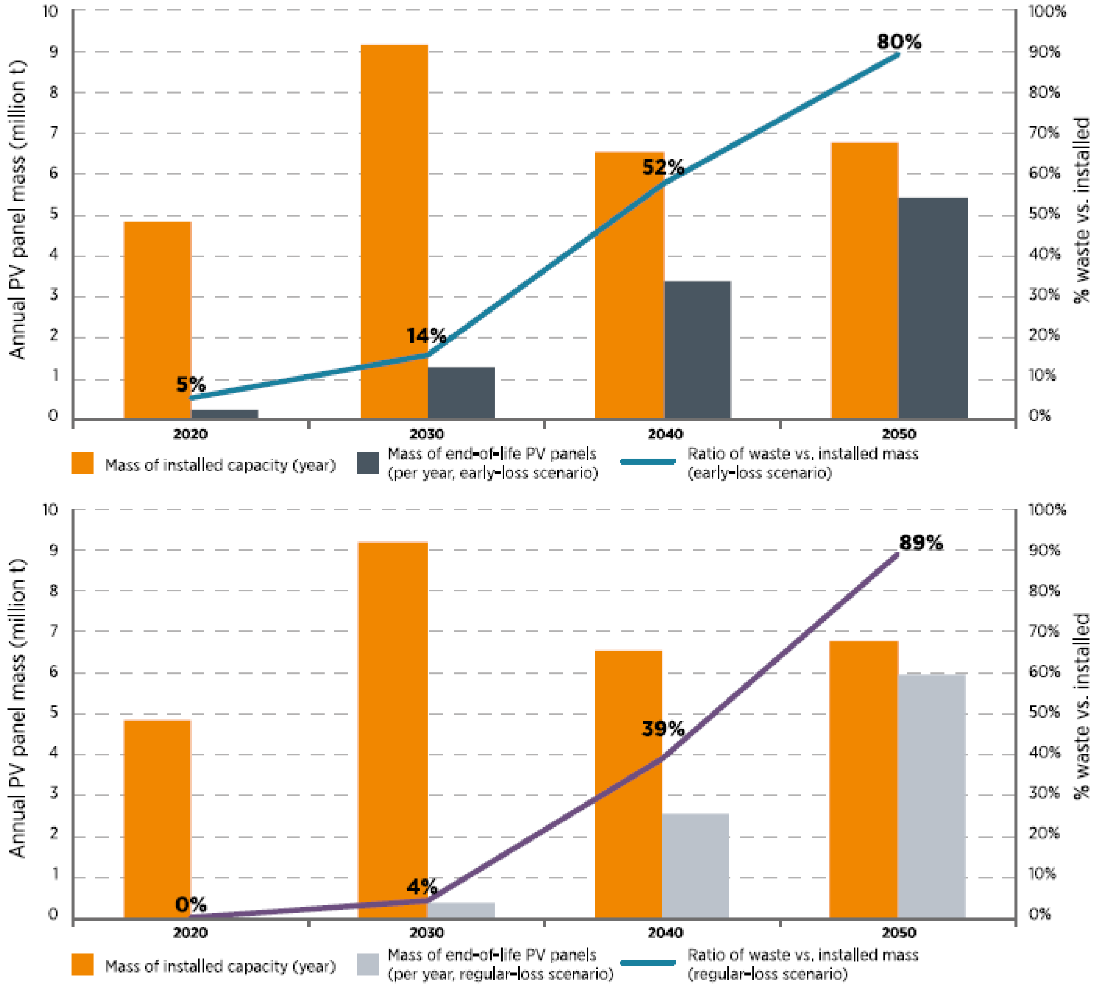


Figure 12 Annually Installed PV vs. PV Waste Projections Early / Regular Loss (from [10])

The above graphs suggest that up until 2030, there will be a faster rate of accumulating PV Panel Waste under the Early-Loss scenario, and after that there will be, gradually, a faster increase in the accumulated PV Waste amounts under the Regular-Loss scenario.

Furthermore, **Table 5** presents detailed PV Panel Waste projected amounts for 2016-2050 for world regions and countries selected according to PV deployment status and expectations for growth.

Table 5 PV Panel Waste Model – Cumulative PV Waste Volumes By Country (Ton) (based on [10])

YEAR	2016		2020		2030		2040		2050	
SCENARIO Regular and Early Loss	Regular Loss	Early Loss	Regular Loss	Early Loss	Regular Loss	Early Loss	Regular Loss	Early Loss	Regular Loss	Early Loss
ASIA										
China	5,000	15,000	8,000	100,000	200,000	1,500,000	2,800,000	7,000,000	13,500,000	19,900,000
Japan	7,000	35,000	15,000	100,000	200,000	1,000,000	1,800,000	3,500,000	6,500,000	7,600,000
India	1,000	2,500	2,000	15000	50,000	325,000	620,000	2,300,000	4,400,000	7,500,000
Republic of Korea	600	3,000	1,500	10,000	25,000	150,000	300,000	820,000	1,500,000	2,300,000
Indonesia	5	10	45	100	5,000	15,000	30,000	325,000	600,000	1,700,000
Malaysia	20	100	100	650	2,000	15,000	30,000	100,000	190,000	300,000
EUROPE										
Germany	3,500	70,000	20,000	200,000	400,000	1,000,000	2,200,000	2,600,000	4,300,000	4,300,000
Italy	850	20,000	5,000	80,000	140,000	500,000	1,000,000	1,200,000	2,100,000	2,200,000
France	650	6,000	1,500	25,000	45,000	200,000	400,000	800,000	1,500,000	1,800,000
United Kingdom	250	2,500	650	15,000	30,000	200,000	350,000	600,000	1,000,000	1,500,000
Turkey	30	70	100	350	1,500	11,000	20,000	100,000	200,000	400,000
Ukraine	40	450	150	2,500	5,000	25,000	50,000	100,000	210,000	300,000
Denmark	80	400	100	2,000	4,000	22,000	40,000	70,000	130,000	125,000
Russian Federation	65	65	100	350	1,000	12,000	20,000	70,000	150,000	200,000
NORTH AMERICA										
United States of America	6,500	24,000	13,000	85,000	170,000	1,000,000	1,700,000	4,000,000	7,500,000	10,000,000
Mexico	350	800	850	1,500	6,500	30,000	55,000	340,000	630,000	1,500,000
Canada	350	1,600	700	7,000	13,000	80,000	150,000	300,000	650,000	800,000
MIDDLE EAST										
United Arab Emirates	0	10	50	100	3,000	9,000	20,000	205,000	350,000	1,000,000
Saudi Arabia	200	250	300	1,000	3,500	40,000	70,000	220,000	450,000	600,000
AFRICA										
South Africa	350	550	450	3,500	8,500	80,000	150,000	400,000	750,000	1,000,000
Nigeria	150	200	250	650	2,500	30,000	50,000	200,000	400,000	550,000
Morocco	0	25	10	100	600	2,000	4,000	32,000	50,000	165,000
OCEANIA										
Australia	900	4,500	2,000	17,000	30,000	145,000	300,000	450,000	900,000	950,000
LATIN AMERICA AND CARIBBEAN										
Brazil	10	10	40	100	2,500	8,500	18,000	160,000	300,000	750,000
Chile	150	200	250	1,500	4,000	40,000	70,000	200,000	400,000	500,000
Ecuador	10	15	15	100	250	3,000	5,000	13,000	25,000	35,000
TOTAL WORLD	43,500	250,000	100,000	850,000	1,700,000	8,000,000	15,000,000	32,000,000	60,000,000	78,000,000
SUM OF LEADING COUNTRIES	28,060	187,255	72,160	668,500	1,352,850	6,442,500	12,252,000	26,105,000	48,685,000	67,975,000
REST OF THE WORLD	15,440	62,745	27,840	181,500	347,150	1,557,500	2,748,000	5,895,000	11,315,000	10,025,000

This thesis concludes it is not surprising that the largest projected PV Waste streams by 2030 will be in Asia, with up to 3 Million Ton, depending on the considered scenario. China will be leading the countries accumulating PV Panel Waste, with an estimated amount between 200.000 Ton and 1,5 Million Ton by 2030, followed by Japan and India. Up until 2050 the Asian continent is expected to accumulate up to 40 Million Ton PV Panel Waste, with China only accumulating up to 20 Million Ton (see **Figure 13**).

In Europe, Germany, with up to 1 Million Ton in 2030 and up to 4,3 Million Ton in 2050, is expected to lead at all times (2016-2050) the list of countries generating PV Panel Waste, which is an intuitive conclusion, based on the fact that Germany has been world leader for installed PV capacity for a long time (until surpassed by China in 2015) and is still the European leader.

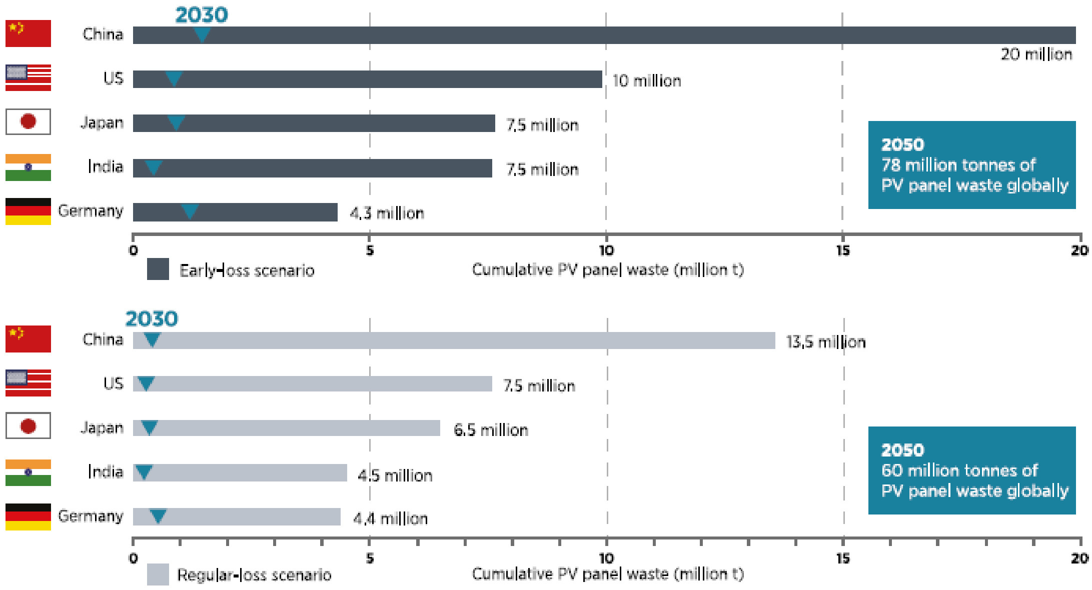


Figure 13 Estimated Cumulative PV Panel Waste By 2050 – Top Five Countries (from [10])

3.9 Economic Value Creation From PV End-Of-Life Phase

There are several options for managing the PV Panels end-of-life, in agreement with the circular economy paradigm of Reduce-Reuse-Recycle (in this priorities order). This section focuses mainly on reporting estimates by IEA PVPS and IRENA on the equivalent monetary value to be potentially obtained from PV recycling business ventures, by recovering raw materials from PV Panels. The other options will be addressed in detail further down, in the main Discussion section.

As of 2016-2017 the amounts of PV Panels at their end-of-life phase are not considered significant enough to justify the starting of large-, or even medium-scale, dedicated, PV Recycling utilities, and the PV treatment and recovery processes happen, generally, at the premises of existing general waste processing plants, or directly at the PV manufacturing sites, e.g. FirstSolar (thin film PV Panels) who operates its own refurbishment and recycling programme and infrastructure, having a direct control on the end-to-end life cycle of their PV Panels **[35]**. However, as the amounts of PV Panel Waste are expected to surge over the next decade (and even more so from 2030 to 2050) it is apparent that considerable, and sustainable economic value and employment opportunities can be created through PV treatment and recycling. EA PVPS and IRENA have estimated globally the potential material value recovered by PV Panel treatment and recycling at 450 Million USD by 2030 (the equivalent of 60 Million new PV Panels), and 15 Billion USD by 2050 (the equivalent of 2 Billion new PV Panels), alone by recovering raw materials from the PV Panels **[10]**.

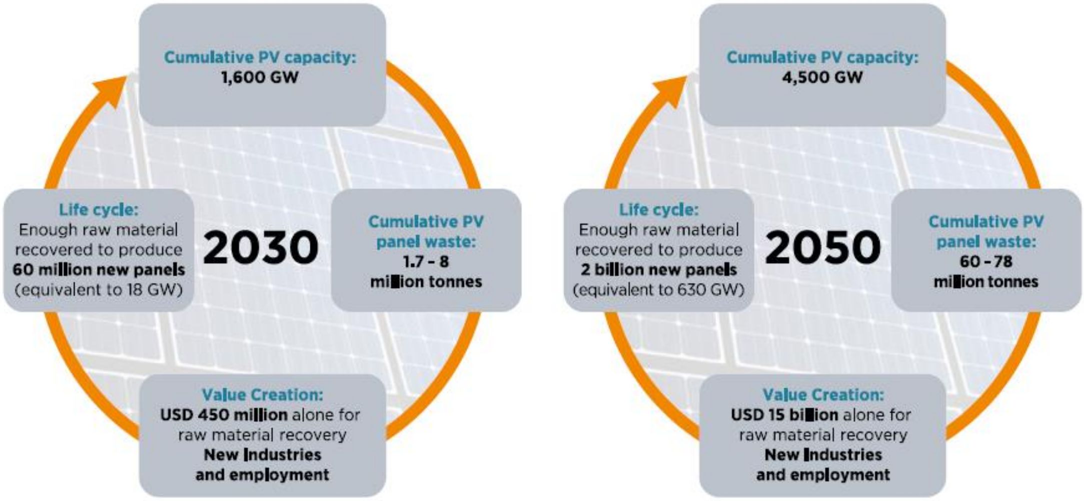


Figure 14 Potential Economic Value Creation From PV End-Of-Life Management (from [10])

It is estimated that, depending on the efficiency of the recycling technologies, almost 1 Million Ton glass could be recovered from PV Panels by 2030 **[10]**, as glass makes up for more than 80% of panel weight. Valued at an average price of 46,3 EUR/Ton (based on Eurostat statistics for 2002-2016, **[35]**), only this recovered glass alone could be worth of more than 45 Million EUR.

Similarly, considerable amounts of aluminum (75.000 Ton) and copper (7.000 Ton) are expected to be recovered through PV Panel recycling by 2030, valued up to 150 Million EUR, based on the last the years average market prices for these commodities (**[37]**, **[38]**), and adding up to the raw material supply available for manufacturing new PV Panels.

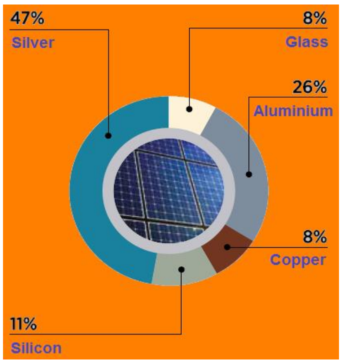


Figure 15 Relative Material Value (%) For c-Si PV Panels (based from [10])

Silver has the greatest economic value in a PV Panel's composition (see **Figure 15**), and although it makes up for less than 0,1% of a PV Panel's weight by mass, it is estimated that about 90 Ton silver could be recovered by 2030 from end-of-life PV Panels, estimated at 50 Million USD, and it could be injected back into the economy to support the production of at least 50 Million new PV Panels **[10]**.

Other materials could also be recovered through PV Panel recycling activities, e.g., nickel, gallium, indium, selenium telluride, etc., adding up to 390 Ton by 2030, equivalent to 180

Million USD and sufficient to support the manufacturing of 60 Million new PV Panels, assuming improved recycling processes which will gradually refine recycling purities for rare elements, and also manufacturing processes with reduced material use.

The above presented figures demonstrate clearly the significant potential to generate economically and environmentally sustainable business activities through sound PV end-of-life treatment and recycling practices, based on the cradle-to-cradle paradigm. In addition to creating economic value, re-using resources and minimizing the amounts of PV Panels that would go directly to disposal landfill sites, also new employment opportunities will be created, in both the public and private sectors. Specific technical skills will be needed for recycling, as well as new education and training programs, which will all contribute to laying a solid foundation for the world's circular economy, in agreement with the Paris Agreement and the UN Sustainable Development Goals.

4 Case Study: LP Model For Environmentally Sustainable PV Recycling

4.1 Introduction

Given the necessity to develop sustainable business models for the management of the PV Systems' end-of-life, in an environmentally sound manner, and in alignment with the Sustainable Development Goals, this case study proposes and discusses in detail a Linear Programming (LP Optimization) Model whose goal is to decide on the most effective allocation of upcoming the PV Waste streams to PV Recycling facilities, based on the environmental footprint of these facilities and the total logistics costs associated with PV Recycling activities.

Germany was for a long time the world leader for installed PV capacity, and it will be, for the long term (2050) one of the world's top five countries, and the European leader, to become PV Panel Waste markets (see **Figure 13**). At the same time, Germany is the most advanced country in the world currently in regards to elaborating and implementing PV Waste management regulations, as well as collection and recycling facilities (based on **[10]**). For these reasons, the present case study focuses on Germany, and specifically on Bavaria, its Southern federal state. More information about Germany's PV industry is presented further down in this document.

The question addressed herein is how should the expected large streams of PV Waste be allocated to PV Recycling facilities in a manner that generates economic value consistently, and minimizes the total transport (Carbon emissions included) and logistics costs associated with the end-of-life phase of the PV panels, based on their expected amount, geographical location, and the year when they need to be sent to recycling facilities. Capital investment costs and operation and maintenance costs for running a PV Recycling facility have been also analyzed in several previous studies (e.g., **[12]**, **[16]**, **[18]**, **[19]**, **[41]**, **[42]**) and will not be further investigated within the current case study.

In a 2010 study, Choi and Fthenakis **[12]**, have proposed a linear optimization model suggesting the optimal geographical locations for PV take-back centers, focusing only on the collection and recycling of PV manufacturing scrap in the eastern federal states of Germany, where the largest German PV manufacturers were located at that time. They emphasized that future models would need to account for all sources of PV Waste. Currently, and also for the future, it is expected that the main sources of PV Waste would actually be due to the end-of-life phase of the PV modules which had been installed in Germany over the past two decades.

Bavaria could be considered Germany's Sunshine state, based on its installed PV capacity, and also based on its solar irradiation conditions, relative to the other German federal states (see **Figure 16**). With a total of 2.359 MWe in 2008, and 11.309 MWe in 2015, Bavaria is by far the federal state with the largest installed PV capacity, averaging 33% of Germany's installed PV capacity between 2008 and 2015 (see **Table 6**).

For these reasons, Bavaria was chosen as geographical and administrative region to provide the dataset used in the Linear Optimization Model.

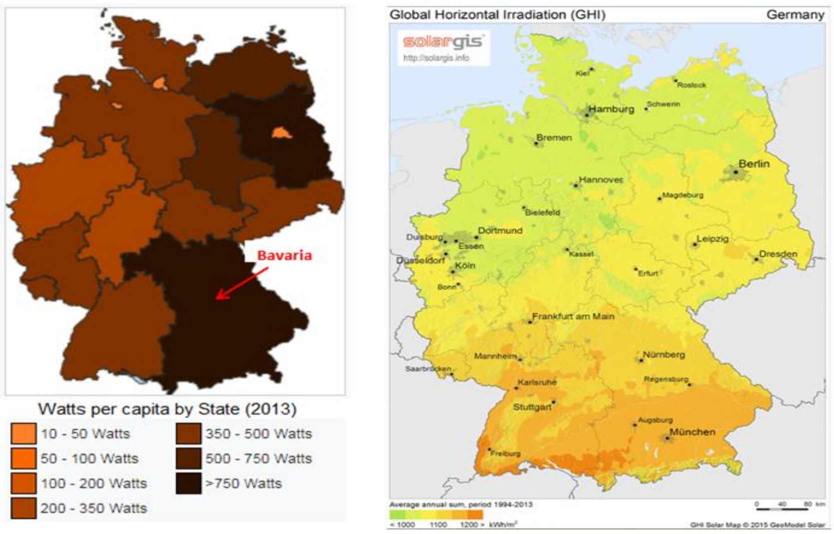


Figure 16 Germany – Installed Solar Capacity W/Capita (2013) and Solar Irradiation (1994-2013)[8]

[8] Compiled from http://solargis.com and the European Photovoltaic Industry Association **[2]**

4.2 Methodology

Based on the list of PV solar power plants and rooftop PV systems installed in Bavaria/Germany (**[3]**[9]), a shorter list was extracted, with the fifty largest solar power plants, from the older power plants (commissioned between 2000-2010), with an installed capacity of 390 MWe. According to their website, Solar-Prinz.de maintain an up-to-date list with the largest PV solar installations in Germany. The year of plant commissioning and the nearest municipality, identified from Google Maps, have been added. Also, the plant operator and the PV Module manufacturer have been included in **Table 19** from **Appendix 1**.

Table 6 Germany – Installed Solar Power Capacity [MW] – 2008-2015 (compiled from [1][10])

GERMANY - INSTALLED SOLAR POWER CAPACITY [MW]								
State	**2008**	**2009**	**2010**	**2011**	**2012**	**2013**	**2014**	**2015**
Bavaria	2.359	3.955	6.365	7.961	9.701	10.425	11.100	11.309
Baden-Württemberg	1.245	1.772	2.907	3.753	5.838	6.112	4.985	5.117
North Rhine-Westphalia	617	1.046	1.925	2.601	3.582	3.879	4.235	4.364
Lower Saxony	352	709	1.479	2.051	3.045	3.257	3.491	3.580
Hesse	350	549	868	1.174	1.521	1.662	1.769	1.811
Rhineland-Palatinate	332	504	841	1.124	1.528	1.671	1.862	1.921
Saxony	168	288	529	836	1.281	1.412	1.575	1.608
Schleswig-Holstein	159	310	695	992	1.352	1.408	1.469	1.498
Thuringia	95	159	327	467	872	1.014	1.120	1.187
Saxony-Anhalt	94	181	450	817	1.378	1.556	1.829	1.963
Brandenburg	72	219	638	1.313	2.576	2.711	2.901	2.982
Saarland	67	100	158	218	319	365	407	416
Mecklenburg-Vorpommern	48	88	263	455	958	1.099	1.338	1.414
Berlin	11	19	68	50	63	69	81	84
Hamburg	7	9	27	25	32	36	37	37
Bremen	4	5	14	30	32	35	40	42
Added Capacity [MW]		**3.933**	**7.641**	**6.313**	**10.211**	**2.633**	**1.528**	**1.094**
Cumulative Total Capacity Installed [MW]	**5.980**	**9.913**	**17.554**	**23.867**	**34.078**	**36.711**	**38.239**	**39.333**
Bavaria % of Total Capacity Installed	**39,45%**	**39,90%**	**36,26%**	**33,36%**	**28,47%**	**28,40%**	**29,03%**	**28,75%**

Residential PV installed capacities and any amounts of PV manufacturing scrap have not been evaluated, and are not included in the calculations of this case study as sources of PV Waste. Future studies would need to account correctly for all sources of PV Waste, and especially for the residential PV which has been growing consistently as installed capacity, over the last decade.

Based on the list described above, 38 administrative locations (the closest municipalities) of the largest PV installations have been identified (see **Table 22** from **Appendix 5**). These municipalities have been considered further as the main Collection Centers (**CC_j**) for PV

[9] http://www.solar-prinz.de/exklusive-tabelle-deutschlands-groste-solaranlagen/ **[3]**
[10] Die Bundesnetzagentur - EEG-Statistikberichte **[1]**

Waste, such as those managed by the Stiftung EAR. Being located near to the selected largest PV installations considered for this study case, the travel distance from the PV solar park, or a rooftop installation, to its associated CC_j has been assumed negligible.

This study also assumes seven major cities across Bavaria, as established locations for PV Recycling Centers (**RC_i**) (see **Figure 17**).

Based on **[10]**, which provides short-, mid-, and long-term PV Waste projections for Germany overall (2020, 2030, 2040), the following **Table 7** has been compiled, with annual PV Waste projections for Germany and Bavaria. A simple linear regression model has been used, after assuming, based on **[10]**, an approximately linear increase in the amount of PV panels installed in Germany during the past two decades.

Two scenarios have been considered by **[10]**, Regular Loss and Early Loss, both modelled with a Weibull distribution, and resulting in a significant difference between the PV Waste amounts projected for each scenario.

The Regular Loss scenario assumed 30-year average lifetime for PV Panels, 99,99% probability of end-of-life after 40 years (a technical assumption based on depreciation times and durability data documented by PV manufacturers).

The Early Loss scenario also assumed 30-year average lifetime for PV Panels, 99,99% probability of end-of-life after 40 years, and in addition it included assumptions such as: 0,5% installation and transport damages, 0,5 % loss of PV panels during the first two years of operations, 2% loss after 10 years, and 4% loss after 15 years of operations.

The fact that the projected PV Waste amounts are so different for these two scenarios emphasizes a critical aspect for the proper planning of PV Recycling facilities: it is utterly important to account, as accurately as possible, as frequently as possible, for the projections of PV Waste amounts, in order to fine-tune the optimization models whose tasks are to allocate optimally any PV Waste streams to recycling facilities. The **Figure 17** provides a zoom-out view for the geographical distribution of the herein proposed (**CC_j**) and (**RC_i**), also relative to the national borders relative to Bavaria.

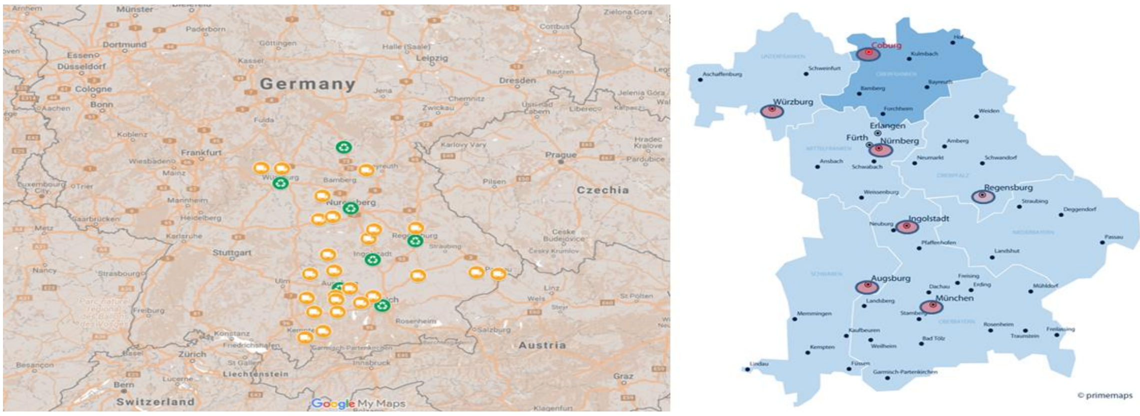


Figure 17 Bavaria - PV Collection & Recycling Centers - Proposed Locations[11]

A more detailed, zoom-in map with proposed locations for PV Collection and Recycling Centers in Bavaria is included in **Figure 34** and the list describing the assumptions used for the Linear Optimization Model and their references is provided in **Table 23**, both located in the **Appendices** section.

Table 7 Germany And Bavaria Cumulative PV Waste Projections 2020-2040[12]

	GERMANY - CUMULATIVE PV WASTE PROJECTIONS [Ton]		BAVARIA - CUMULATIVE PV WASTE PROJECTIONS [Ton]	
YEAR	REGULAR LOSS	EARLY LOSS	REGULAR LOSS	EARLY LOSS
2020	**20.000**	**200.000**	**6.600**	**66.000**
2021	58.000	280.000	19.140	92.400
2022	96.000	360.000	31.680	118.800
2023	134.000	440.000	44.220	145.200
2024	172.000	520.000	56.760	171.600
2025	210.000	600.000	69.300	198.000
2026	248.000	680.000	81.840	224.400
2027	286.000	760.000	94.380	250.800
2028	324.000	840.000	106.920	277.200
2029	362.000	920.000	119.460	303.600
2030	**400.000**	**1.000.000**	**132.000**	**330.000**
2031	580.000	1.160.000	191.400	382.800
2032	760.000	1.320.000	250.800	435.600
2033	940.000	1.480.000	310.200	488.400
2034	1.120.000	1.640.000	369.600	541.200
2035	1.300.000	1.800.000	429.000	594.000
2036	1.480.000	1.960.000	488.400	646.800
2037	1.660.000	2.120.000	547.800	699.600
2038	1.840.000	2.280.000	607.200	752.400
2039	2.020.000	2.440.000	666.600	805.200
2040	**2.200.000**	**2.600.000**	**726.000**	**858.000**

11 Source: Roxana Predoiu, based on GoogleMaps and PrimeMaps.de
12 Source: Roxana Predoiu: Linear regression based on information from **[10]**

A travel distance matrix between all the proposed (**CC_j**) and (**RC_i**) has been calculated with Google Maps and is provided in **Table 22**, in the **Appendices** section. The fastest traffic routes have been selected, on the usual truck roads across Bavaria.

The specific transport costs and transport emissions have been calculated with the model presented with full details in **Table 20** in the **Appendices** section. It was assumed that for all distances travelled to transport PV Waste during the PV end-of-life phase a 10 Ton Heavy Duty Truck running on Diesel, with a maximum 5 Ton payload capacity, is to be used. A vehicle fuel efficiency of 34 Liter/100 km has been assumed (based on **[5]**) and a Diesel fuel price of 1,15 EUR/Liter has been assumed (based on **[4]**).

An average salary of 15 EUR/Hour has been assumed for the truck driver (based on **[7]**), and an average truck driving speed of 60 km/Hour. Additionally, an overhead logistics services fee of 1,5 has been included in the calculation of overall logistics costs for all transported PV Waste amounts, to recycling centers, and to final disposal sites (Landfill).

The model foresees all specific travel distances, however, the travel distances from the herein considered sources of PV Waste (**PV_k**) to any Collection Center (**CC_j**), or to any Recycling Center (**RC_i**), have been assumed negligible. This is because one of the simplifying assumptions above is that all PV Waste Collection Centers (**CC_j**) are located in municipalities near the largest PV solar parks and rooftop PV installations included in this case study.

The emissions associated with all the transport of the PV Waste amounts (**CC_j** to **RC_i**, and **RC_i** to **LF_l**) such as greenhouse gas emissions (GHG), Nitrous Oxides (NOx), Sulphur Dioxide (SO2) and Particulate Matter PM) have been calculated with the model documented in **Table 20** from the **Appendices** section, and based on www.ecotransit.org **[11]**.

An uniform distance of 25 km has been considered between any **RC_i** and its closest landfill site **LF_l**, an assumption which would likely be subjected to high variation in further real life scenarios, based on the chosen location for every RC_i, and its distance to the nearest landfill site. This distance has been used in the Optimization Model to calculate the transport and emissions costs for the final disposal of PV Waste amounts to the landfill site, i.e. for the transport of the residual waste after the PV recycling process. The Optimization Model is prepared to include in its calculations any distance values fed into it for this purpose.

The transport related emissions have been calculated as absolute amounts (Ton) and also as monetary value, assuming a Carbon Tax of 20 EUR/Ton CO2. A Carbon Tax has been under intense discussions in Germany lately, being considered by many experts, as mandatory for a successful Energy Transition (EnergieWende), i.e., in order to meet Germany's specific transition targets, in a timely manner. Energy transition experts consider a tax of 20 EUR/Ton CO2 as floor value (the lowest value) which could be relevant for the

EnergieWende targets, as a result of the Emissions Trading System (ETS) price falling to a meaningless value of 4 EUR/Ton CO2 during the last 2016 quarter **[13]**.

Overall, a specific transport cost (fuel, driver, logistics) of 0,1531 [EUR/Ton PV Waste/ km], and a specific transport related Carbon Emissions cost of 0,0015 [EUR/Ton PV Waste/ km] have been derived (see **Table 20**), and taken into account for all further calculations in the Linear Optimization Model.

The amounts of PV Waste considered in the model have been estimated based on the values from **Table 6**, **Table 7**, **Table 19**, and **[10]**. The latter reference approximates a PV Panel Weight-to-Power Ratio of 120 [Ton PV Panel/MWe] for a PV Panel manufacturing the year 2000 (+/-).

The Landfill Gate Fee plus Landfill Tax used by the model have been estimated at 110 [EUR/Ton], based on current reports from WRAP **[8]** and CEWEP (Confederation of European Waste-To-Energy Plants **[9]**.

The mathematical formulation for the proposed Linear Optimization Model is defined with full details in **Table 8**, and it is important to first browse the defined indices, nomenclature and parameters, in order to understand the argumentations provided further down.

The model is implemented with the Solver Module of the Microsoft Excel 2010, using a Simplex LP algorithm, which executes a number of automated iterations before it decides what PV Waste amounts (from a given total PV Waste amount available for recycling) should be allocated to any of the considered **RCi**, in order to minimize the total transport, logistics and emissions costs. Other linear programming solvers could be more appropriate for larger datasets, and considering even more parameters, e.g., GAMS CPLEX, GUROBI, MOSEK, and XPRESS (all requiring a software license), and also open source solvers, e.g. CBC, etc. **[14]**.

All PV Waste amount which need to be sent to PV recycling facilities, in terms of: direct transport (from $\mathbf{PV_k}$ to $\mathbf{RC_i}$, or transport from $\mathbf{PV_k}$ to $\mathbf{CC_j}$, and then from $\mathbf{CC_j}$ to $\mathbf{RC_i}$, as well as transport of any residual amounts (following the recycling process) from $\mathbf{RC_i}$ to $\mathbf{LF_l}$, are accounted for separately. In some cases it may be more efficient to transport the PV Waste amounts from their original source ($\mathbf{PV_k}$) directly to a $\mathbf{RC_i}$, bypassing any $\mathbf{CC_j}$.

Specific transport and logistics costs are also accounted for separately in the model, in cases when, e.g. the transport would be done with different kids of vehicles (in terms of total weight in motion), which would imply different fuel efficiencies, and different emissions. For simplicity, all the scenarios analyzed herein, assume the same specific transport/logistics and emissions costs with a 10 Ton Diesel truck (5 Ton maximum payload), regardless of the direction of the transport (from $\mathbf{CC_j}$ to $\mathbf{RC_i}$, from $\mathbf{PV_k}$ to $\mathbf{RC_i}$, from $\mathbf{PV_k}$ to $\mathbf{CC_j}$ or from $\mathbf{RC_i}$ to $\mathbf{LF_l}$).

For every $\mathbf{CC_j}$ and $\mathbf{RC_i}$ the maximum annual storage and processing capacities are considered (θ_j and respectively ψ_i). For the $\mathbf{RC_i}$ also a processing efficiency (η_i) is taken into account. The current maximum reported recycling efficiency of a PV Recycling facility for silicon-based PV modules is from PV Cycle, 96%, achieved in 2016 **[15]**. The current availability from the maximum capacity of RCi (γ_i) is considered in the model but assumed at 100% for all Scenarios executed herein.

The Objective Function (see expression **(1)** in **Table 8** below) contains three main terms, in the following order: (1) the total costs (transport, logistics, emissions) for any transport of PV Waste amounts from $\mathbf{PV_k}$ to $\mathbf{RC_i}$; (2) the total costs for any transport of PV Waste amounts from $\mathbf{CC_j}$ to $\mathbf{RC_i}$; and (3) the total costs for any transport of residual amounts, after recycling, from $\mathbf{RC_i}$ to $\mathbf{LF_l}$. The minimization of the sum of these three factors is the scope of the objective function.

Three constraints are defined below for this model.

The whole PV Waste amount collected at any $\mathbf{CC_j}$ must be sent to recycling to available $\mathbf{RC_i}$, inequation **(2)** in **Table 8** below.

The sum of all PV Waste amounts to be sent to any $\mathbf{RC_i}$ at a certain moment in time cannot exceed the processing capacity available at that $\mathbf{RC_i}$, at that moment, inequation **(3)**.

Only positive values are valid for the PV Waste amounts allocated by the Linear Optimization Model for recycling to any $\mathbf{RC_i}$, inequation **(4)**.

Table 8 Linear Optimization Mathematical Model

Indices:

i	Loc. index for a Recycling Center	($\boldsymbol{RC_i}$)	$i \in \{1, ..., I\}$
j	Loc. index for a Collection Center	($\boldsymbol{CC_j}$)	$j \in \{1, ..., J\}$
k	Loc. index for PV Waste Source	($\boldsymbol{PV_k}$)	$k \in \{1, ..., K\}$
l	Loc. index for the Landfill Site for $\boldsymbol{RC_i}$	($\boldsymbol{LF_l}$)	$l \in \{1, ..., L\}$

Parameters:

$\boldsymbol{d_{ji}}$	Travel Distance from CC_j to RC_i	(Kilometer)
$\boldsymbol{d_{ki}}$	Travel Distance from PV_k to RC_i	(Kilometer)
$\boldsymbol{d_{kj}}$	Travel Distance from PV_k to CC_j	(Kilometer)
$\boldsymbol{d_{il}}$	Travel Distance from RC_i to LF_l	(Kilometer)
$\boldsymbol{tc_{ji}}$	Specific Transp. Cost from CC_j to RC_i	(EUR/Ton/Kilometer)
$\boldsymbol{tc_{ki}}$	Specific Transp. Cost from PV_k to RC_i	(EUR/Ton/Kilometer)

tc_{kj}	Specific Transp. Cost from PV_k to CC_j	(EUR/Ton/Kilometer)
tc_{il}	Specific Transp. Cost from RC_i to LF_l	(EUR/Ton/Kilometer)
lc_{ji}	Specific Logistics Cost from CC_j to RC_i	(EUR/Ton)
lc_{ki}	Specific Logistics Cost from PV_k to RC_i	(EUR/Ton)
lc_{kj}	Specific Logistics Cost from PV_k to CC_j	(EUR/Ton)
lc_{il}	Specific Logistics Cost from RC_i to LF_l	(EUR/Ton)
X_{ji}	PV Waste amount transported from CC_j to RC_i	(Ton)
X_{ki}	PV Waste amount transported from PV_k to RC_i	(Ton)
X_{kj}	PV Waste amount transported from PV_k to CC_j	(Ton)
θ_j	Maximum (annual) storage capacity for CC_j	(Ton)
ψ_i	Maximum (annual) processing capacity for RC_i	(Ton)
η_i	Processing (recycling) efficiency for RC_i	(%)
γ_i	Current availability of maximum capacity of RC_i	(%)

Objective Function: Minimize Total Transport, Logistics and Emissions Costs:

$$\left\{\sum_{k=1}^{K}\sum_{i=1}^{I} X_{ki}(tc_{ki}d_{ki} + lc_{ki})\right\} + \left\{\sum_{j=1}^{J}\sum_{i=1}^{I} X_{ji}(tc_{ji}d_{ji} + lc_{ji})\right\} + \left\{\sum_{i=1}^{I}(1-\eta_i)\left(\sum_{j=1}^{J} X_{ji} + \sum_{k=1}^{K} X_{ki}\right)(tc_{il}d_{il} + lc_{il})\right\} \quad (1)$$

Subject to following constraints:

$$\sum_{i=1}^{I} X_{ji} = \theta j, \quad \forall\, j \in \{1 \ldots J\} \quad (2)$$

$$\left(\sum_{j=1}^{J} X_{ji} + \sum_{k=1}^{K} X_{ki}\right) \le \gamma_i \psi_i, \quad \forall\, i \in \{1 \ldots I\}, \forall\, j \in \{1 \ldots J\}, \forall\, k \in \{1 \ldots K\} \quad (3)$$

$$X_{ji}, \quad X_{ki}, \quad X_{kj} \ge 0, \quad \forall\, i \in \{1 \ldots I\}, \forall\, j \in \{1 \ldots J\}, \forall\, k \in \{1 \ldots K\} \quad (4)$$

The current version of this model does not account for any Investment Costs, operational and maintenance costs related to the recycling activities in the RCs, revenues obtained from the PV Recycling activities. The economic viability of PV Recycling ventures have been already investigated by a number of studies, e.g., **[10]**, **[12]**, **[15]**, **[16]**, **[18]**, **[19]**. Instead, this model focuses on the optimal allocation of PV Waste amounts to PV Recycling facilities in order to minimize the overall transport, logistics and emissions costs.

Four Scenarios, described with full details in Table 9 below, have been executed with the above defined Linear Optimization Model. The results are discussed in the next section, and are also included with full details in Table 10.

The Base Scenario was used to first test the model, and to evaluate it with a subset of the Bavaria PV plants estimated to generate an amount of PV Waste of approx. 30.000 Ton by year 2024 (assuming 25 years until PV panel EoL), and a subset of 25 CCs with their corresponding PV amounts expected to be collected in 2024. These 25 CCs (extended to 30 CCs in further scenarios) are considered to cover Bavaria reasonably well, in terms of their closeness to existing large PV plants. Seven RCs have been considered in total, as pre-existing, based on distances from major cities in Bavaria. Two model runs have been executed for the Base Scenario: (1) using RC1, RC2, RC4, RC5, RC6, RC7; and (2) using RC1, RC2, RC3, RC5, RC6, RC7.

Scenario #1 considers a forecasted PV amount of approx. 60.000 Ton for Bavaria overall (based on linear regression from values forecasted by IRENA & IEA PVPS for Germany, for Regular and Early Loss scenarios). The list of CCs has been extended from 25 to 30 PV Waste collection points.

Scenario #2 performs a Sensitivity Analysis, starting from the model setup from Scenario 1 above, and considering RC1, RC3, RC4, RC5, RC6, RC7 as PV Recycling facilities (each of them ready to process 20.000 Ton of PV Waste per year) for the approx. 60.000 Ton PV Waste expected in Bavaria for 2024. The scope of this analysis was to investigate how would the Linear Optimization Model change the PV Amounts allocated to individual RCs based on their reported PV Recycling efficiency at that time, and based on changes in the Specific Transport Costs (due to e.g., fuel price changes, truck driver salary changes, potential changes for a Tax Carbon, changes of costs to Landfill, etc.), while keeping the Distance Matrix fixed.

Scenario #3 considers a longer-term linear optimization for the total transport, logistics and emissions costs, instead of looking at just one year of information. For simplicity, only 10 CCs (CC4, CC11, CC12, CC22, CC23, CC26, CC28, CC29, CC31 and CC35) have been selected, as the nearest ones to two particular RCs: RC2 (Coburg) and RC3 (Ingolstadt). It is considered that in the first 3 years of activities, the following CCs would collect annually much larger PV Waste amounts (due to the more PV Panels installed earlier in the areas nearby these particular CCs): CC11, CC22, CC26, CC29, CC35. However, the situation changes after the first three years, and the following CCs would collect, starting with 2027, much more PV Panel waste than the previously mentioned CCs: CC4, CC12, CC23, CC28, CC31. Basically, this scenario accounts for variations over time in the streams of PV Waste to be collected at CCs, depending on the amount of PV Panels installed in particular regions, every year, over several years.

Table 9 Scenarios: Linear Optimization Of Logistics Costs For Processing PV Waste

GERMANY / BAVARIA - PV WASTE [Ton] ALLOCATION TO PV RECYCLING CENTERS - LINEAR OPTIMIZATION SCENARIOS	
SCENARIO YEAR	**SCENARIO Description and Result Interpretation**
BASE **2024**	The Base Scenario was used to first test the LP model, and to evaluate it with a subset of the Bavaria PV plants estimated to generate an amount of PV Waste of approx. 30.000 Ton by year 2024 (assuming 25 years until PV panel EoL), and a subset of 25 CCs with their corresponding PV amounts expected to be collected in 2024. These 25 CCs (extended to 30 CCs in further scenarios) are considered to cover Bavaria reasonably well, in terms of their closeness to existing large PV plants. Residential PV amounts and PV manufacturing scrap have not been evaluated for this case study (in terms of amounts x geographical coordinates) but are assumed to be within short distances from the selected CCs. Seven RCs have been considered in total, as pre-existing, based on distances from major cities in Bavaria. Two model runs have been executed for the Base Scenario: (1) using RC1, RC2, RC4, RC5, RC6, RC7; and (2) using RC1, RC2, RC3, RC5, RC6, RC7. **Parameter Values** : PV Panel Waste Transport Cost = 0.1531 [EUR/Ton/ km]; Landfill Gate Fee plus Landfill Tax = 110 [EUR/Ton]; Specific Cost due to Transport related Carbon Emissions 0,0015 [EUR/Ton/ km] assuming a Carbon Tax of 20 [EUR/Ton Carbon]. All proposed RCs have been assumed with 90% recycling efficiency, but with different processing capacities /year (see the Results Table). For ALL Scenarios it was assumed the transport of PV Waste is done with a 10 Ton Heavy Duty Vehicle with a maximum payload of 5 Ton (this was used for calculation of emissions from transport as well). From these runs, it resulted that it would be slightly cheaper to use RC4 instead of RC3 in 2024, resulting in lower overall logistics costs and Carbon emissions.
#1 **2024**	This Scenario considers a forecasted PV amount of approx. 60.000 Ton for Bavaria overall (based on linear regression from values forecasted by IRENA & IEA PVPS for Germany, for Regular and Early Loss scenarios). The list of CCs has been extended from 25 to 30 PV Waste collection points. **Parameter Values** : PV Panel Waste Transport Cost = 0.1531 [EUR/Ton/ km]; Landfill Gate Fee plus Landfill Tax = 110 [EUR/Ton]; Specific Cost due to Transport related Carbon Emissions 0,0015 [EUR/Ton/ km] assuming a Carbon Tax of 20 [EUR/Ton Carbon]. All six selected RCs are considered from now on at 20.000 Ton annual processing capacity, in expectation of swiftly increasing flows of PV Waste, on annual basis. Assumed 95% recycling efficiency for all RCs. Two model runs have been executed for the Scenario: (1) using RC1, RC2, RC4, RC5, RC6, RC7; and (2) using RC1, RC3, RC4, RC5, RC6, RC7. From these runs, it resulted that when all RCs have the same processing capacity of 20.000 Ton/Year, it would be slightly cheaper to use RC3 (Ingolstadt) instead of RC2 (Coburg) in 2024, resulting in lower overall logistics costs and Carbon emissions. However, RC2 (Coburg, a more remote center in the Northern part of Bavaria, close to the border with Thuringia) would become important for the upcoming years, when increasing amounts of PV Waste will be expected to be processed at RCs.
#2 **2024**	This Scenario performs a Sensitivity Analysis, starting from the model setup from Scenario 1 above, and considering RC1, RC3, RC4, RC5, RC6, RC7 as PV Recycling facilities for the approx. 60.000 Ton PV Waste expected in Bavaria for 2024. The scope of this analysis was to investigate how would the LP Model (who's target is to minimize the Total Transport/Logistics related Costs) change the PV Amounts allocated to individual RCs based on their reported PV

GERMANY / BAVARIA - PV WASTE [Ton] ALLOCATION TO PV RECYCLING CENTERS - LINEAR OPTIMIZATION SCENARIOS	
SCENARIO YEAR	**SCENARIO Description and Result Interpretation**
	Recycling efficiency at that time, and based on changes in the Specific Transport Costs (due to e.g., fuel price changes, truck driver salary changes, potential changes for a Tax Carbon, changes of costs to Landfill, etc.), while keeping the Distance Matrix fixed. **Parameter Values** : the Transport Specific Costs have been changed in 10% increments from -30%...30% deviation starting from the initial value, see in Scenario 1. Also, for each one of the six selected RCs, the recycling efficiency has been varied (95%, 90%, 85%), while all the other five RCs remained at 95% efficiency.
#3 **2024-2028**	This Scenario considers a longer-term linear optimization of total transport costs, instead of looking at just one year of information. For simplicity, only 10 CCs (CC4, CC11, CC12, CC22, CC23, CC26, CC28, CC29, CC31 and CC35) have been selected, as the nearest ones to two particular RCs: RC2 (Coburg) and RC3 (Ingolstadt). **Parameter Values** : it is considered that in the first 3 years of activities, the following CCs would collect annually much larger PV Waste amounts (due to the more PV Panels installed earlier in the areas nearby these particular CCs): CC11, CC22, CC26, CC29, CC35. However, the situation changes after the first three years, and the following CCs would collect, starting with 2027, much more PV Panel waste than the previously mentioned CCs: CC4, CC12, CC23, CC28, CC31. Basically, this scenario accounts for variations over time in the streams of PV Waste to be collected at CCs, depending on the amount of PV Panels installed in particular regions, every year, over several years.

4.3 Results And Analysis

From the two runs executed in the Base Scenario, for a total amount of approximately 30.000 Ton PV Waste to be recycled in 2024, and based on the assumed processing capacities for the seven RC_i, it resulted that it would be slightly cheaper for the environment to use RC4 instead of RC3 in 2024, resulting in lower overall transport & logistics costs and Carbon emissions. Using RC3 in 2024 would result in 178 Ton Carbon/Year from all road transport activities, as opposed to 162 Ton Carbon/Year, when involving RC4 instead. The average % usage of the RC_i processing capacity was only 68,42%, suggesting that the RCs had been oversized, for the available PV Waste amounts in 2024. However, as Scenario 3 will highlight further down, it is important to consider the design of RC capacity not only short-term, but also mid-, and long-term, as the streams of PV Waste may have very diverse dynamics, based on geographical location, year of PV System installation, PV Module type and manufacturer.

Table 10 Results: Linear Optimization Of Logistics Costs For Processing PV Waste

GERMANY / BAVARIA - PV WASTE [Ton] ALLOCATION TO PV RECYCLING CENTERS - OPTIMIZATION SCENARIOS																		
SCENARIO	PV Waste Amount [TON/YEAR]	RC Usage of FULL CAPACITY [%]	RC_1 [TON/YEAR]		RC_2 [TON/YEAR]		RC_3 [TON/YEAR]		RC_4 [TON/YEAR]		RC_5 [TON/YEAR]		RC_6 [TON/YEAR]		RC_7 [TON/YEAR]		Total RC Logistics Costs [EUR / YEAR]	Total RC Transp. Carbon Emissions [Ton Carbon / YEAR]
			Allocated	Capacity	Allocated	Capacity	Allocated	Capacity	Allocated	Capacity	Allocated	Capacity	Allocated	Capacity	Allocated	Capacity		
BASE	29.080	68,42%	2.500	2.500	896	10.000	0	0	10.000	10.000	5.000	5.000	5.000	5.000	5.684	10.000	980.442	162
	29.079	68,42%	2.500	2.500	896	10.000	10.000	10.000	0	0	3.870	5.000	4.911	5.000	6.902	10.000	1.048.363	178
#1	57.827	48,19%	20.000	20.000	1.940	20.000	0	0	10.811	20.000	8.616	20.000	11.028	20.000	5.432	20.000	987.326	236
	57.827	48,19%	20.000	20.000	0	0	11.247	20.000	3.224	20.000	6.896	20.000	11.028	20.000	5.432	20.000	954.839	224
#2	**Sensitivity Analysis** performed for changes in the PV Waste amounts allocated by the LP Optimization Model to each individual RC when the Distance Matrix was fixed but Specific Transport Costs and PV Recycling Efficiencies were varied. The results are presented numarically and graphically in the Table and Graphs pertaining to the Sensitivity Analysis. From this Scenario it resulted: RC1 - the Distance Matrix seems to have a greater influence on how PV Waste amounts are allocated to this RC, for an overall optimal Transport Costs solution. However, the allocated amounts decreased more than half when RC1 was considered to perform at a lower efficiency (85%). RC3 - was the most sensitive RC to changes in the specific transport costs and processing efficiency than RC1. It has not received any PV Amount allocated for processing when its efficiency was at 85%, except for the situation when specific transport costs were 30% over the base value (but even in this case, the amount received for processing was only 10% of its full capacity). RC4, RC5 and RC6 - were moderately sensitive to variations in specific transport costs and processing efficiencies. RC7 - was not influenced at all in any variations in specific transport costs and processing efficiencies. The maximum PV amounts allocated to each individual RC corresponded to the cases when they performed at 95% efficiency, with some differences in allocation, based on variations in the specific transport costs. Full Results (detailed numerical values and graphical representations) are presented further down in Table "**Impact On PV Waste Allocated to RCi When Varying Transport Cost and Recycling Efficiency**" and Figure "**Sensitivity Analysis – PV Waste Allocated to RCi –Visual Guide To Relative Amounts**".																	
#3	Executed only for two RCs (RC_2 and RC_3), over 5 years, this Scenario resulted in lower (by 10%) Logistics Costs and Transport Emissions when efforts for planning the RCs take into account longer term PV Waste projections (stream of PV Waste flow by type, amount, geographical location and expected year of becoming waste and necessary to be sent to recycling). Shorter term projections, or highly inaccurate projections of PV Waste (e.g. underestimated) would result in less than optimal PV Recycling facilities design (capacity and location). For a (central, non-profit) governmental organization, tasked with the monitoring of, and the reduction of environmental impacts of business activities (e.g. PV Recycling), it is essential that planning efforts are improved as much as possible, by collecting data as accurately as possible, planning short, mid-, and long-term, for the minimization of environmental costs while generating important economic value from business activities, as well as social aspects, such as employment. For detailed numerical Results Please see **Appendix "Impact Of Recycling Center Capacity Design On Total Logistics Costs"**.																	

Cucchiella *et al*. (2015) **[16]** have performed a financial analysis of PV Recycling facilities for the Italian PV ecosystem, and argued for the optimal recycling plant size (capacity) related to current and expected national PV Waste amounts. They found that, in the Italian context, economic profitability can be achieved in the case of thin film PV Modules, in PV Recycling plans with at least 20.000 Ton/year processing capacity.

Scenario #1 herein considered all RCs having the same processing capacity (20.000 Ton/year) and the same processing efficiency (95%). From the two executed runs, (1) using RC1, RC2, RC4, RC5, RC6, RC7; and (2) using RC_1, RC3, RC4, RC5, RC6, RC7, it resulted that it would be slightly cheaper to use RC_3 (Ingolstadt) instead of RC_2 (Coburg) in 2024, due to lower overall transport, logistics and Carbon emissions costs. However, RC2 (Coburg, a more remote center in the Northern part of Bavaria, close to the border with Thuringia) would become important for the upcoming years, when increasing amounts of PV Waste will be expected to be processed at RCs.

For Scenario #2, the Sensitivity Analysis, the specific transport costs have been adjusted in 10% deviation increments (from -30% to 30%) starting from their initial value (as in Base Scenario). Also, for each one of the six selected RCs, the recycling efficiency has been varied (95%, 90%, 85%), while all the other five RCs remained at 95% efficiency. A total amount of 57.800 Ton PV Waste needed to be transported for recycling, in an optimal manner, from thirty CCs to six selected RCs. The numerical parameters and results are included in **Table 11**, and a visual guide for the relative size of the PV Waste amounts allocated by the Linear Optimization Model is displayed in **Figure 18.**

Table 11 Sensitivity Analysis: RC_i Allocated PV Waste Due To Transp.Costs & Recycl. Efficiency

Transport Cost [EUR/Ton/KM] Deviation	RC_i Efficiency if all other RCs = 95%	RC_1 Amount	RC_3 Amount	RC_4 Amount	RC_5 Amount	RC_6 Amount	RC_7 Amount
-30,00%	**95,00%**	20.000	11.247	3.224	6.896	11.028	5.432
-20,00%	**95,00%**	20.000	11.247	3.224	6.896	11.028	5.432
-10,00%	**95,00%**	20.000	11.247	3.224	6.896	11.028	5.432
0,00%	**95,00%**	20.000	11.247	3.224	6.896	11.028	5.432
10,00%	**95,00%**	20.000	11.247	3.224	6.896	11.028	5.432
20,00%	**95,00%**	20.000	11.247	3.224	6.896	11.028	5.432
30,00%	**95,00%**	20.000	11.247	3.224	6.896	11.028	5.432
-30,00%	**90,00%**	8.331	1.960	2.089	3.606	7.891	5.432
-20,00%	**90,00%**	20.000	1.960	2.089	3.606	7.891	5.432
-10,00%	**90,00%**	20.000	4.885	2.089	4.516	7.891	5.432
0,00%	**90,00%**	20.000	4.885	2.089	6.896	7.891	5.432
10,00%	**90,00%**	20.000	6.445	2.089	6.896	7.891	5.432
20,00%	**90,00%**	20.000	6.445	2.089	6.896	7.891	5.432
30,00%	**90,00%**	20.000	6.445	2.089	6.896	7.891	5.432
-30,00%	**85,00%**	8.331	0	0	3.606	7.891	5.432
-20,00%	**85,00%**	8.331	0	1.019	3.606	7.891	5.432
-10,00%	**85,00%**	8.331	0	2.089	3.606	7.891	5.432
0,00%	**85,00%**	8.331	0	2.089	3.606	7.891	5.432
10,00%	**85,00%**	8.331	0	2.089	3.606	7.891	5.432
20,00%	**85,00%**	8.331	0	2.089	3.606	7.891	5.432
30,00%	**85,00%**	8.331	1.960	2.089	3.606	7.891	5.432

Clearly, for year 2024 there was some overcapacity at the existing RCs, and it was expected that some of them would not receive enough PV Waste amounts to fulfill their full processing capacity. However, RC1 was the only facility to receive 20.000 Ton of PV Waste / year for processing, but only when its recycling efficiency was 95% or 90%. For all cases when its efficiency was 85%, or it was 90% but the specific transport costs dropped by 30% from the Base Scenario value, the PV Waste amount allocated to RC1 dropped to 8.300 Ton, which means less than half of its full annual capacity. For RC5, RC6 the optimization model was more sensitive to changes in the specific transport costs due to, e.g., higher Carbon taxes, or higher fuel prices, when compared to changes in the RC processing efficiency. RC7 receives always the same PV Waste amount for recycling (5.400 Ton/year), regardless of variations in transport costs and processing efficiency, which indicates, that based on the geographical location of PVk (sources of the PV Waste to be recycled in 2024) this RC7 facility, at 20.000 Ton/year, is almost four times oversized. The PV Waste amounts allocated optimally to RC3 and RC4 are impacted by both factors Transport costs and efficiency). Particularly RC4 was completely excluded from optimal allocations in all cases when its processing efficiency was only at 85%. In fact, for the PV Waste stream available for processing in 2024 only RC1 would be able to function at its full capacity if its recycling efficiency ≤ 90%.

This kind of sensitivity analysis is valuable also for long term planning when surely at least the transport & logistics (and perhaps also emissions) costs would suffer variations over time. As Scenario 2 showed, this will impact the optimal allocation of scope of work for the existing RCs.

Finally, Scenario #3 makes the transition from static (one year) evaluations of the Linear Optimization Model to a longer term evaluation, which should be in fact the approach in real-life applications. The results are detailed in **Table 24**, in the **Appendices** section. Executed, for simplicity, only for two RCs (RC2 and RC3), over 5 years, this Scenario resulted in a reduction (by 10%) of the total transport, logistics and emissions costs when efforts for planning the RCs take into account longer term PV Waste projections (stream of PV Waste flow by type, amount, geographical location and expected year of becoming waste and necessary to be sent to recycling), instead of planning initially e.g., for less than three years of activities. For transporting an amount of 122.300 Ton PV Waste to the two selected RC facilities for recycling during a five years time period, resulted in 3.612.000 EUR total transport & logistics & emissions costs when one of the RCs (RC2) was initially designed with only 10.000 Ton processing capacity /year, based on the forecasted PV Waste amounts for the first three years (2024-2026). When the expected PV Waste amounts were evaluated for five years (2024-2028) it became obvious that sizing RC2 at 20.000 Ton processing capacity/year would be more economical (and more environmentally sustainable in any case) for the whole five years period, as the total transport & logistics & emissions costs declined by 10%.

Figure 18 Sensitivity Analysis – PV Waste Allocated to RC_i –Visual Guide To Relative Amounts

The main message derived from this scenario is that shorter term projections, or highly inaccurate projections of PV Waste (e.g. underestimated) would result, overall, in less than optimal PV Recycling facilities design (capacity and geographical location). Perhaps it may seem beneficial initially, when evaluating the result for a shorter period of time, but since investment capital is involved in opening such recycling facilities, and it’s not facile to close them down in one place and then open new ones at another location, from one year to the next, it becomes apparent how important is for these emerging business activities to rely on long-term, reliable, forecasting in regards to the expected streams of PV Waste based on the following attributes: (1) in which year is to be expected, (2) which type (PV Module technology), (3) what amount of PV Waste, and (4) in which region, with a granularity as fine as possible for each one of these attributes.

From the perspective of a PV Recycling business owner the extra 10% increase in transport costs (OPEX) over five years (as in the example above) perhaps would not be a major issue, as the business may even record higher EBITDA (Total Revenue minus OPEX), depending on the PV Waste streams received for processing. However, for a (central, non-profit) governmental agency, tasked with the monitoring and the reduction of environmental impacts from business activities such as PV Recycling, it is essential that planning efforts are improved as much as possible, by collecting PV Waste related data as accurately as possible, and by planning short, mid-, and long-term, in order to minimize the environmental costs while generating important economic value from these business activities, and contributing to social aspects (e.g., creating employment).

This case study proposed a relatively simple yet robust methodology, and it could have great practical value, provided that the datasets fed into it are accurate, complete, and aim at covering also long-term scenarios.

The next question, however, is who would actually have the greatest interest in using such a model which decides where the PV Waste amounts should be sent for recycling. The first intuitive answer is that, again, a central, governmental, non-profit agency, e.g., Stiftung EAR in Germany, empowered by the Federal Ministry of Environment, would be the appropriate choice to: (1) evaluate continuously the upcoming streams of PV Waste (based on the four attributes introduced above); (2) regularly evaluate the performers, i.e. the PV Recycling facilities, especially for their environmental performance; (3) decide on the optimal allocation of annual PV Waste amounts for recycling, while focusing on the minimization of environmental costs; (4) advise parties interested in starting PV Recycling activities in a certain region in regards to the applicable regulations, the expected short-, mid-, and long-term streams of PV Waste (amounts and types), and consequently, advise them about the appropriate processing capacity for such facilities. These aspects will be reiterated in more detail in the main Discussion section of the document.

Before concluding this case study, it is important to consider also further model improvements, or model extensions, and a few proposals are introduced herein.

So far it was considered that the decision on the optimal allocation of PV Waste amounts to the specific PV Recycling facilities is done once per year, e.g. before the beginning of a new business year. In real life this assumption may not hold, and the decision on optimization may have to be more dynamical (e.g. on monthly basis), including continuous feedback loops of information (e.g., about remaining storage capacity, remaining processing capacity, etc.), concerning all involved actors: PV_k, CC_j, RC_i, LF_l, transport companies, official environmental legislation. Therefore, at least the available capacity γ_i (as % of the full capacity) of any functional RCi should be accounted for in the model (herein it was assumed at 100% at any time). For simplicity, all PV Waste transport has been assumed as done with a 10 Ton Heavy Duty Vehicle on Diesel (with maximum payload of five Ton), and the specific transportation costs have been calculated for this vehicle type. In real life different vehicles (type, capacity) may be employed, and the specific transport costs and emissions must be accounted for correctly, for every case. The current Linear Optimization Model foresees all these parameters separately, but they have not been used with different values in the executed scenarios. Also, it is possible that by 2024 several developed and developing countries would have adopted already, to a considerable extent, freight road transport not based on fossil fuels (e.g. Germany), as part of their ongoing Energy Transition, in an effort to curb transport-related GHG emissions. Other countries (especially less developed, or developing countries) may lag behind such transformation, therefore this could be an additional factor to be accounted for in the optimization model (as well in future legislative and regulatory frameworks) in order to increase the motivation for promoting freight road transport free of fossil fuels.

Furthermore, the current Linear Optimization Model, had only one objective function in its mathematical formulation (see **Table 8**), but it could be relatively easy enhanced for multiobjective optimization, by using Goal Programming. This refers to multiple criteria decision making (MCDM) and it's rather a generalization of linear programming, aiming to satisfy several goals defined by a decision maker, while handling, in an optimal manner, multiple decision criteria which could be conflicting and having different priorities **[17]**.

For example, the assumed central entity, responsible primarily for the environmental sustainability of PV Recycling activities, would have set certain limits on the emissions resulted from the transport of PV Waste amounts; or limits on the residual amounts of PV Waste which would be sent, after recycling, for final disposal at landfill sites; or certain benchmark values for the overall environmental performance of a PV Recycling facility (e.g., a weighted score which accounts for resource usage, such as water, electricity, usage of fossil fuels, recycling efficiency, efficiency and purity from recovering rare elements, etc.); or goals for the business revenue derived from these activities. These objective measures could be assigned different priorities in the Goal Programming Model, based on the vision, the responsibilities and the constraints of the respective central entity (e.g. the 2030 sustainable development, or Energy Transition targets).

5 Discussion: Practical Options For The Sustainable PV Life Cycle

This thesis considers that pursuing a sustainable business model, in a sense that economic value and social benefits are generated while the environment is protected, within well defined objectives, benefits from adopting a systems thinking paradigm where the system's stakeholders, components and boundaries are well known, the linkages and the interactions between them are well understood, and can be controlled. An integrative approach would cut across several business areas and stakeholders interests', system boundaries may be subjective, but it is apparent that in order to be successful in managing the end-of-life phase for PV Systems, the entire PV ecosystem as a whole needs to be optimized along the three core dimensions of sustainability.

The previous sections have argued (based on literature review) that PV end-of-life could generate very valuable business opportunities, and a linear programming model was proposed in order to allocate the PV Panel Waste amounts to PV Recycling facilities in an optimal manner for the environment preservation, i.e. by minimizing the total transport and logistics costs (transport emissions included) associated with the PV Panel's recycling and disposal phase.

Perhaps among all 17 SDG's, SDG 12 (Sustainable Consumption and Production) is the one that best represents the focus of this section, which takes further the discussion about possible pathways to manage the PV end-of-life (but not limited to end-of-life) in a sustainable manner (several options are addressed in detail, within the following sub-sections).

Some of the targets of SDG12 particularly relevant herein are as follows: (4) "*By 2020, achieve the environmentally sound management of chemicals and all wastes throughout their life cycle, in accordance with agreed international frameworks, and significantly reduce their release to air, water and soil in order to minimize their adverse impacts on human health and the environment*", (5) "*By 2030, substantially reduce waste generation through prevention, reduction, recycling and reuse*", (6) "*Encourage companies, especially large and transnational companies, to adopt sustainable practices and to integrate sustainability information into their reporting cycle*", and (9) "*Support developing countries to strengthen their scientific and technological capacity to move towards more sustainable patterns of consumption and production*" **[44]**.

5.1 Photovoltaics Ecosystem Map

Figure 19 below provides a diagrammatic perspective of the sustainable Photovoltaics ecosystem, with its stakeholders and artefacts which interact with, and impact the PV Systems' at defined moments during their overall life cycle.

As mentioned before, system boundaries are contextual and may be subjective. This means, a thorough and accurate PV ecosystem analysis needs to look also beyond the ‘borders’.

For example, a set of environmental regulations applies in a certain EU country (including the PV end-of-life management), e.g. a Carbon Tax which is quantified as an EUR value/Ton $CO2_{eq}$. This country already has some operational PV Recycling facilities but there are also PV Recycling facilities, close to the political border, in one of its neighbouring countries where the Carbon Tax has not been enacted yet. Without a central authority to carefully oversee possible ‘system leakages’, the entities responsible for the proper management of the end-of-life PV Systems in the first country may choose to ‘move’ their PV recycling activities across the border, where they would not have to pay Carbon Taxes for any transport of the PV Panel Waste. This may not be illegal, but it is certainly not fair because: (1) the first country has a competitive disadvantage, although it complies with environmental sustainability rules; (2) the environmental sustainability goals for the region (regardless of the national political borders)) are not fulfilled.

However, sustainability, along its three dimensions, must transcend political borders, therefore, in order for such scenarios to be properly detected and controlled one must carefully analyze the (PV) ecosystem also across its blurred boundaries.

Another such example refers to PV Manufacturers which have put PV Panels on markets in countries other than the manufacturer’s original country. The sub-section **Business Models And Financing Mechanisms** below will explain how the EU regulatory approach has dealt with such cases, in order to correctly assign the responsibility for the PV end-of-life management.

Figure 19 Photovoltaics Ecosystem Map[13]

5.2 The Reduce-Reuse-Recycle Paradigm

The largest part of this thesis focuses on the sustainable end-of-life management of PV Panels, which refers to the collection, transport, treatment, recycling and eventually final disposal of amounts of PV Panel Waste. However, in order to create a sustainable cradle-to-cradle life cycle for PV Systems we must focus also on the other two dimensions of a circular economy: Reduce and Repair. In fact, the desired, decreasing order of priorities in a circular economy is: Reduce, Repair (& Reuse), Recycle (see **Figure 20**).

As the world population keeps growing, and we are entering the era of a new Industrial Revolution (Industry 4.0, with an exponentially growing number of interconnected electric and electronic devices), the world's energy demand is also projected to increase significantly, for example, by 30% up until 2040 **[22]**. Although currently the global supplies for most materials used for the manufacturing of PV Panels are not under stress of resource scarcity, unavoidably, resource shortages will occur as the world will gradually increase its production of electronic equipment, including PV Panels. It is therefore apparent that RnD

[13] Source: Roxana Predoiu

and PV manufacturers focus on reducing material use, material substitutions, and improving efficiencies. Potential improvements in this regard have been described extensively in literature (e.g., [20], [23], [28]), and have also been already discussed in the Photovoltaic Technologies Review section herein.

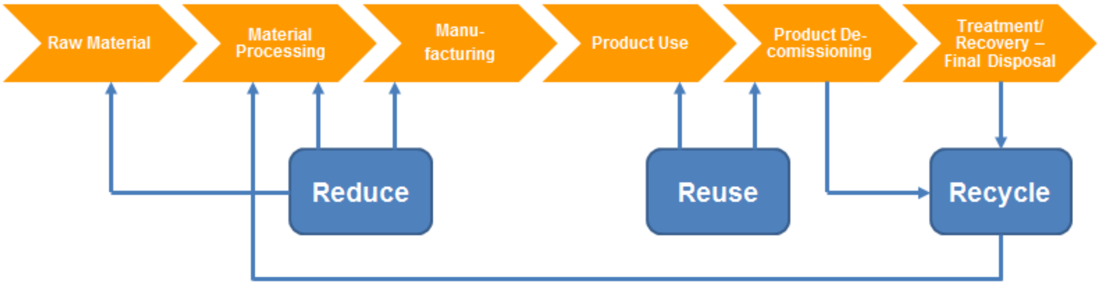


Figure 20 PV Panels Life Cycle Stages And The 3R Paradigm[14]

As most PV Systems have been installed during the last six years (from 15 GW global installed PV capacity in 2008 to 222 GW in 2015 and 300 GW in 2016 – described above in the document), it means most of these systems would likely reach their end-of-life around year 2045. According to the Early-Loss scenario, there could be however already a number of infant, or even midlife failures among the installed PV Panels. As they would be covered by guarantees, typically any defective PV Panels (not broken because of careless manipulation by the Customer) would be returned to the manufacturer, or affiliated service centers, for inspection and potential repair. Repair and Reuse are the preferred options, before any Recycling and ultimate disposal.

As documented by [10], a series of tests need to be done in order to determine the defective status, and try to repair and eventually resell the PV Panels, or some of their components, as second hand products: quality tests to check the electrics and the power output; a flash test characterization and a wet leakage test; perhaps applying a new frame, new junction box, new diodes, plugs and sockets could resolve the problem; solar cells may also be replaced and relamination is also possible. The 'restored' product would be rebranded (to indicate that it is a pre-owned PV product which has been refurbished, or repaired), relabeled (mandatory requirements for e-waste Producers), it would receive a new guarantee, and it could be resold at a reduced market price, of approximately 70% of the original sale price [10]. There are already a few informal emerging online markets that facilitate the selling of such products (see an additional discussion on this topic further down, in the section on Blockchain market for PV products).

The (PV) Recycling option is the least preferred option in the 3R paradigm and as of 2016 there has not been a significant global PV Waste market (due to the relatively young age of

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[14] Source: Roxana Predoiu, based on literature review

most installed PV Panels), and consequently, with a few notable exceptions (e.g. PV Cycle, First Solar), there have not been many dedicated PV Recycling facilities involved with the PV Panels end-of-life and typically the recycling of PV Panels happens currently at general recycling facilities, where also products such as mirrors, windscreens, laminated glass, LCDs and screen glass, among others, are recycled. This situation will start to change considerably after 2025, and the business venture of PV Recycling will become much more economically viable.

It has been already described in previous sections that applying high-value PV recycling processes could generate significant socio-economic benefits, due to the value of the recovered raw materials, and also for creating employment opportunities. Additionally, Monier and Hestin (2011, **[40]**) have argued that, compared with a scenario where no specific treatment or recycling are applied, the environmental impact of end-of-life PV Panels could be reduced by a factor of four when including residential PV Panels under the WEEE regulatory framework, and reduced by a factor of six when including all end-of-life PV Panels under the WEEE Directive **[32]**.

PV Recycling technologies have been researched and improved during the past 15 years by a number of PV manufacturers, RnD, academia, etc., such as: First Solar (specifically for thin film CdTe panels, see **Figure 21**), Deutsche Solar (predominantly for c-Si PV Panels), BP Solar, Siemens Solar, PV Cycle, the Brookhaven National Laboratories in US, Nedo in Japan, and several others.

The first major step in PV recycling consists of the mechanical separation of the major components and materials and it typically results in high rates of material recovery by panel mass, but materials which contribute in smaller % to the panel's weight and which may be rare, and have higher values /unit mass, may not be satisfactory recovered (**[10]**, **[40]**).

The process for recycling laminated glass consists of the following steps: pre-crushing, manual sorting, magnetic separation, fine crushing, screening, separation of non-ferrous material, extraction, colour-based sorting, resulting eventually in glass cullet, foil, and fine grain foil products.

Based on this information, the current thesis considers that PV Recycling technologies are undergoing a learning curve, as any technology, and they will need to be continuously fine-tuned not only to increase recycling efficiencies and enhance the purity of the recovered raw materials, but also in order to keep up with the innovations and technological changes in the PV Panel manufacturing sector, as well as any targets set through environmental regulations, e.g., the mandatory collection rates stipulated by the WEEE recast directive **[32]**. Such recycling technologies will have to improve their recovery rates for major elements (by weight), such as glass, aluminum, copper, as well as expensive materials used in smaller amounts. Last, but not least, efforts will be needed to improve the safe recovery of hazardous materials, e.g., cadmium, and overall, to reduce the PV amounts that will be subjected to final disposal at landfill sites.

As [10] reports, one of the major technical challenges that still needs to be overcome is the delamination, or the removal of the EVA encapsulant, with several options explored so far: mechanical crushing, thermal processing, organic solvents, pyrolysis and vacuum blasting.

First Solar has started the recycling of its CdTe PV Panels back in 2003, at their manufacturing locations. They have been recycling primarily the manufacturing scraps, and also sold PV Panels. They have a recycling program, prefunded through an Escrow-like account, at the sale of the PV Panels, to cover the collection, transport and recycling of each sold PV Panel (for the time period 2003-2009 First Solar have set aside 86 Million USD for the collection and recycling of PV Panels). The collection and transport services are free for their customers ([35], [40]). First Solar's thin film PV panels recycling process is schematically presented in **Figure 21**.

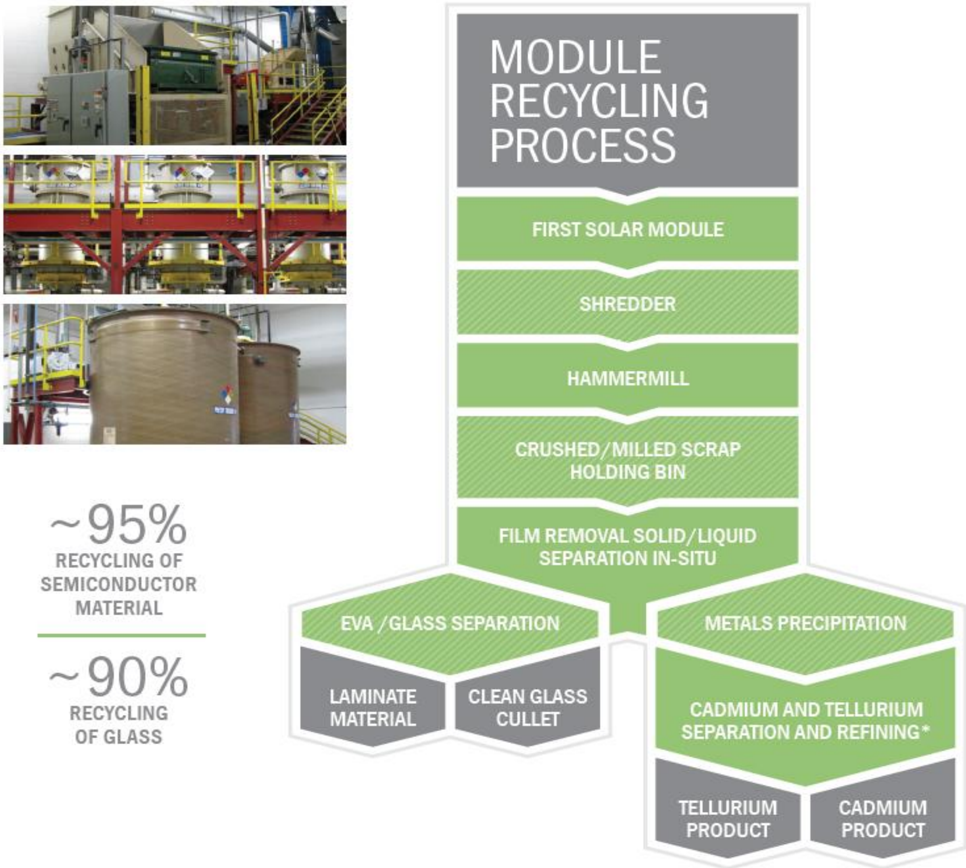

Figure 21 First Solar Thin Film PV Panel Recycling Process (from [35])

5.3 Business Models And Financing Mechanisms

This section is based on literature review (sources indicated with square brackets) combined with the author's reasoning, and it presents different business models options and financing mechanisms with potential to contribute to the sustainable governance of the PV Systems' end-of-life phase. Firstly, some general considerations are introduced, then a set of options are discussed in detail, and finally, the current status is described for some of the top PV player countries.

A general recipe is not in the scope of this discussion, since adopting one or another type of business model depends heavily on a series of complex factors (e.g., the maturity of WEEE relevant regulations and institutions in a certain country, or region, the socio-political arena, the total installed PV Systems capacity and their average age, the public perspective and general compliance concerning e-waste collection and recycling, etc.). The current discussion, however, attempts to provide a common denominator to serve as practical methodology guidelines, especially for countries and/or regions where PV Recycling processes have not been started yet (or not to a significant extent). Such guidelines could help setting the stage for the initiation of these business activities, in a timely manner, and focused on sustainability concerns, by leveraging on the experience of countries which are currently more advanced with the PV end-of-life management.

Starting from the PV Ecosystem Map (see **Figure 19**), the focus is narrowed down to three main actors: the PV Producers, the PV Costumers (B2B – business to business, or B2C - business to consumer, as private households), and the Public (represented by the society in general, government and non-government organizations, municipalities, public infrastructure, regulations). The first question that needs to be addressed is: who's responsibility is to deal with the PV Panels end-of-life? The descriptions of currently implemented solutions are summarized along with their pros and cons, in **Table 12** below.

It is apparent that, regardless of what business model is eventually adopted, any waste management approaches (PV Panel Waste included) are based on the following main areas of concern **[10]**:

- A physical system for the collection, storage, dismantling, transport, treatment, recovery, recycling and ultimate disposal. The end-of-life PV Panels may be initially gradually gathered at some general collection centers, then transferred to a more central and specialized location where they could be subjected to physical dismantling and some primary separation processes into material groups (e.g., metals, glass, plastics, wiring, etc.) by trained personnel. Then they are transported to dedicated recycling facilities where hazardous materials are separated from raw materials which could be re-injected into the commodities markets, or re-used in the economy, depending on the recovered purity. Depending on the recycling efficiency, a certain fraction of the initial amounts of PV Panel Waste may have to travel and be disposed of at dedicated landfill sites (depending on the material composition and local environmental regulations).

- A financial processing and reporting system, which keeps track of the amounts and types pf PV Panel Waste processed for their end-of-life, the amounts and types of recovered materials, the amounts and types of hazardous materials, the system costs and the revenues obtained from the recycling activities, the prefunding financial amounts paid by PV Manufacturers who have put PV products on the market during a certain time period (e.g. one calendar year), etc.
- A management and financing System which oversees the overall management for PV Panels end-of-life and ensures that system rules are followed and objectives are fulfilled (e.g. the fulfillment of the dedicated environmental KPIs).
- The regulatory approach, developed by international, national, or regional jurisdictions, and which defines specific regulations and policies addressing the management of the PV Systems' end-of-life phase.

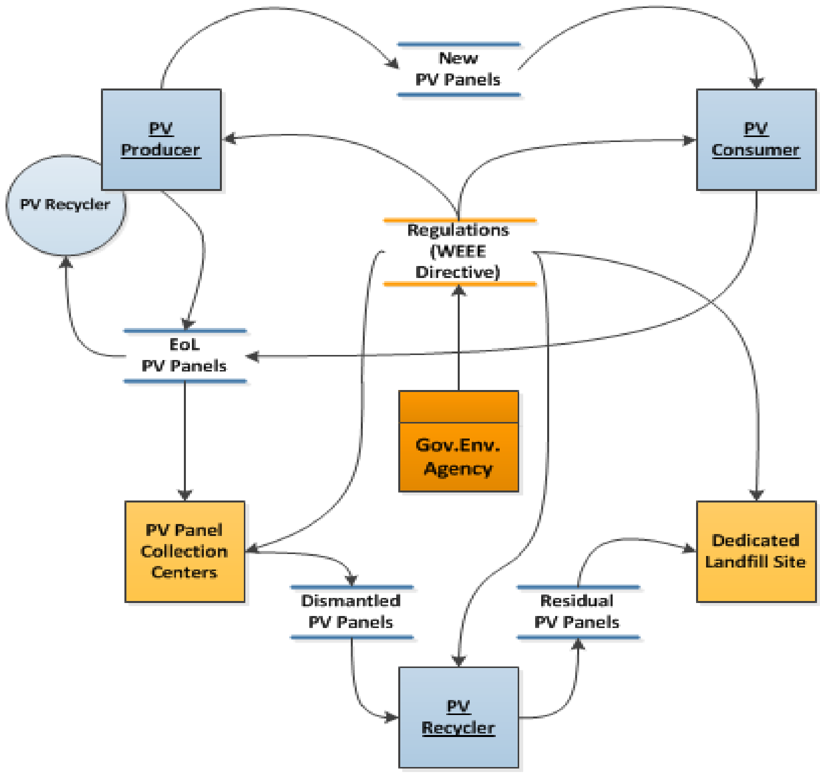

Figure 22 PV End-Of-Life Data Flow Diagram[15]

[15] Source: Roxana Predoiu

Table 12 Options For PV End-Of-Life Responsible Entities[16]

PV EoL Resp. Entity	Process Description Advantages / Disadvantages
PV Customer (B2B, B2C)	The final Consumer, user of the PV Panels, generates the PV Panel Waste and is responsible for its end-of-life management: transport to collection and storage facilities (pick-up, or bring-in services), or to treatment & recycling facilities; the fees for proper treatment and any ultimate disposal of the PV Waste. The (recycling) fees may be be collected upfront (at the time of purchasing the PV Panels), or at the end-of-life of the PV Panels, when the Customer pays the entity in charge for recycling treatment, and disposal services. **<u>PROs:</u>** - in countries where environmental protection is an established priority in the public perspective (i.e. environmentally minded citizens), and where the % of system cheaters is expected to be small, this option could ensure that PV Panel Waste collection rates are high and the right fees are collected for recycling. **<u>CONs:</u>** - generally, since PV Producers are not directly involved in financial matters concerning the PV end-of-life, they may lack the motivation to strive for a design with the thought of PV Panels end-of-life phase in mind, in order to simplify and improve technical recycling processes, i.e., lacking the motivation to contribute to SDG 12 (responsible production and consumption). - in any countries where a public environmental conscience and also environmental regulations are not so well developed yet, or not properly enforced, the end-customers might be tempted to dump the PV Panels and skip any end-of-life responsibility altogether.
PV Producer	By virtue of the EPR = Extended Producer Responsibility paradigm (already adopted by EU countries based on the WEEE 2012 Directive, and followed by other countries in the world), the PV Producers are responsible for their products throughout their life cycle, and thus, by joining (or developing themselves) a compliance scheme, to ensure (physically and financially) the proper collection and end-of-life treatment of their PV Panels. Two financing approaches: (1) PAYG (pay-as-you-go) + 'Last Man Standing' Insurance and/or 'Joint-and-Several Liability' scheme. The cost of logistics and recycling treatment is paid by PV Producers active on the market at the moment when the PV Waste occurs. The "Joint-and-Several Liability" scheme means that producers of a certain product, or group of products, come together and accept the liabilities for waste collection and recycling for the respective product(s). (2) PAYP (pay-as-you-put). PV Producers must make un upfront payment when they place their products on the market, in order to prefund the collection and end-of-life treatment for these products. **<u>PROs:</u>** - the PV Producers may be incentivized to develop more environmentally friendly PV Panels, easier and cheaper to be managed at their end-of-life. - PAYG + 'Last Man Standing' Insurance or 'Joint-and-Several Liability' scheme are considered more cost effective and more common nowadays. - PAYP might incentivize PV Producers to invest in new technologies, resulting in leaner and greener recycling processes if the fees they need to pay upfront for collection and recycling are not calculated in a general manner, but conform with the specific costs involved with recycling a PV Producer's

16 Source: Roxana Predoiu, partially based on [10]

PV EoL Resp. Entity	Process Description Advantages / Disadvantages
	panels. Likely this could be addressed by determining the recycling costs and efficiencies for a specific PV product (as part of a certification scheme, e.g., by TüV). Thus, the PV Producer pays upfront less recycling fees is his product performs cheaper and better at recycling tests. **<u>CONs:</u>** - pre-funding approach (PAYP) is considered to work better only for specific e-waste and in lower quantities. - depending when a country adopts the specific regulation (e.g. , implementation of a WEEE 2012 Directive), there may be amounts of PV Panels which are not covered by PAYP, because they were put on the market before the regulation was adopted, therefore no prefunding has been made for them, and the original PV Producers may even not be active anymore. Although there are approaches to deal with this situation, this would complicate the financial offsetting among the current PV market participants and/or the Public. - PAYP upfront payments may become disproportionate with the ultimate costs for collection and recycling, as the PV end-of-life phase will occur on average 30 years later, and recycling technologies may have evolved considerably meanwhile.
Public	Governmental organizations and municipalities, representing the public interest, are involved with the organization, controlling and management of the PV Panels end-of-life operations. The financial aspects would be covered by taxation. **<u>PROs</u>**: - revenue could be created for the involved municipalities through the recovered value from recycling activities (recovered raw materials, re-injected into the economy). Additional costs could be avoided by using existing public infrastructure. Also jobs could be added in the public sector. **<u>CONs</u>**: - PV Producers may be slower in incorporating innovation and improving their product design-for-end-of-life, and focus more on quick profits rather than on environmental preservation targets. - lack of competition and expertise from the private sector, as well as reduced motivation for seeking overall cost optimizations.

In addition to **Table 12**, it is worth mentioning that currently there are some PV Producers (e.g., First Solar) which operate directly their own recycling facilities, following a voluntary approach, free-of-charge for the end-Customers, based on which they collect and recycle the PV Systems they put on the market, along with their manufacturing scrap and any production faulty PV panels. The **Figure 22** presents schematically a dataflow diagram specific to the PV Panels' end-of-life, and according to the main areas of concern described above.

Based on **[10]**, the European Union (EU) is currently (by the end of 2016) the only entity which has defined and enacted specific regulations concerning the PV Systems' end-of-life management.

The revised WEEE Directive 2012/19/EU represents currently the most advanced regulation framework which has been specifically designed to foster a level playing field for all e-waste producers (including the PV market participants) and to ensure that, on the long run, the activities for the collection and recycling of PV Panel Waste streams are conducted in a sustainable manner (economic-social-environment benefits) in the 28 EU Member States. It introduces the extended-producer responsibility principle (EPR), which translates roughly into: PV producers which put PV products on markets in EU Member States are legally responsible to finance the end-of-life collection and proper recycling activities for their products, regardless where the products were manufactured.

The waste from electrical and electronic equipment (WEEE), which now includes also PV Panel Waste, is considered one the fastest growing waste streams in the EU, with approx. 9 Million Ton generated in 2005, and expected to exceed 12 Million Ton by 2020. Because the WEEE represents a complex mixture of materials including hazardous content which can cause major environmental and health issues if not properly managed, the EU has created two pieces of legislation: The Directive on waste electrical and electronic equipment (WEEE Directive) and the Directive on the restriction of the use of certain hazardous substances in electrical and electronic equipment (RoHS Directive) **[45]**.

The first WEEE Directive (Directive 2002/96/EC) entered into force in February 2003 and it was foreseeing the establishment of collection schemes supporting the end-users for disposing free-of-charge of their WEEE. Due to complex challenges posed by the ever increasing WEEE streams, the European Commission enacted a recast of the WEEE Directive (2012/19/EU) which became effective in February 2014.

The RoHS Directive 2002/95/EC which restricts the use of hazardous materials in electrical and electronic equipment entered into force in February 2003 and it stipulates that heavy metals (e.g., lead, mercury, cadmium, hexavalent chromium, flame retardants such as polybrominated biphenyls –PBB, or polybrominated diphenyl ethers -PBDE) must be substituted with less hazardous materials **[45]**.

The WEEE Directive has increased gradually the WEEE collection and recovery targets, as it is presented in **Table 13** below. Herein recovery refers to the physical reclamation of a specific material, or fraction, from the general WEEE stream, whereas recycling refers to undertaking specific activities for the treatment and reuse of the recovered materials. The Directive specifies quotas and treatment requirements, as well as requirements for EEE producers to label their products diligently, and provide information about environmental impact and proper end-of-life treatment of their products, for end-users and equipment end-of-life treatment entities.

One of the most important definitions, and consequently classification and responsibility assignment, provided by the recast Directive (2012/19/EU) refers to 'Producers' (herein specifically referring to PV Manufacturers), as follows **[32]**:

"*'Producer' means any natural or legal person who, irrespective of the selling technique used, including distance communication within the meaning of Directive 97/7/EC of the*

European Parliament and of the Council of 20 May 1997 on the protection of consumers in respect of distance contracts (1):

(i) is established in a Member State and manufactures EEE under his own name or trademark, or has EEE designed or manufactured and markets it under his name or trademark within the territory of that Member State;

(ii) is established in a Member State and resells within the territory of that Member State, under his own name or trademark, equipment produced by other suppliers, a reseller not being regarded as the 'producer' if the brand of the producer appears on the equipment, as provided for in point (i);

(iii) is established in a Member State and places on the market of that Member State, on a professional basis, EEE from a third country or from another Member State; or

(iv) sells EEE by means of distance communication directly to private households or to users other than private households in a Member State, and is established in another Member State or in a third country."

Table 13 The WEEE Directive Evolution For WEEE Annual Collection And Treatment Rates[17]

	Annual collection targets	Annual recycling/Recovery targets
Original WEEE Directive (2002/96/EC)	4 kg/inhabitant	75% recovery, 65% recycling
Revised WEEE Directive (2012/19/EU) up to 2016	4 kg/inhabitant	Start with 75% recovery, 65% recycling, and 5% increase after 3 years
Revised WEEE Directive (2012/19/EU) from 2016 to 2018	45% (by mass) of all equipment put on the market	80% recovered and 70% prepared for reuse and recycled
Revised WEEE Directive (2012/19/EU) from 2018 and beyond	65% (by mass) of all equipment put on the market or 85% of waste generated	85% recovered and 80% prepared for reuse and recycled

IEA PVPS and IRENA **[10]** anticipate the WEEE Directive will soon undergo additional revisions and extensions, by imposing efficiency improvements, high-value and high-yield WEEE treatment processes, which will be accomplished by RnD efforts and further adoption also by the emerging PV Recycling industry. All EU Member States have enacted the recast WEEE Directive into national legislation, with, or without adding certain country-specific adaptations. Such legislation is essential for the development of circular economies and it

[17] Based on **[10]**, **[45]** and **[32]**

could serve as example for other countries and regions with installed PV capacity around the world.

The PV Systems' life cycle, with the WEEE Directive as central stakeholder, is depicted in **Figure 23** through causal loops (not exhaustive of all possible connections, because of lack of space), where the positive links (in green) represent causality and a positive correlation between two elements A and B (i.e. an increase in A will trigger an increase in B, and a decrease in A will trigger a decrease in B), and the negative links (in red) represent causality and a negative correlation between two elements (an increase in A will trigger a decrease in B, and a decrease in A will trigger an increase in B). The dotted cloud suggests conceptually an open system, which has interactions also with other external systems and entities, not depicted herein.

For example, between "Electricity Supply" and "Electricity Demand" there are two red (negative) links, meaning: as the electricity generation increases (e.g. due to increases in the installed PV capacity), it results in a (compensatory) decrease in the electricity demand, whereas the increase in electricity demand (e.g. due to increases in economic growth as well as progress with deploying Industry 4.0 applications and progress in the Energy Transition in the Transport and the Heating & Cooling sectors, etc.) will reduce the electricity supply. Similarly, a red, negative link represents the relationship between increases in "PV Recycling Efficiency" resulting in decreasing amounts of PV Waste being disposed of at Landfill sites, whereas a positive (green) link between "Incentives for EoL Product Design" and "New Technology /Innovations" means that, as the PV Producers & PV RnD are specifically incentivized for this purpose, they will focus increasingly on designing products using less raw materials, or new and non-hazardous materials, and which could be recycled easier, and with increased recycling efficiencies. As "PV Recycling Efficiencies" increase, the "Raw Material Resources Availability" will also increase (a green, positive link), and this will also stimulate the "Economic Growth", because raw materials recovered through recycling processes will be re-injected into the economy. Also, investments in new, improved technologies will likely result in delaying the onset of PV Panels' end-of-life phase (a red, negative link). Increases in: innovation, RnD efforts to develop new technologies, deploying Industry 4.0 applications, economic growth and environmental sustainability projects, will all facilitate new Job Opportunities, and contribute to the social dimension of a sustainable system.

One major benefit of adopting a systems thinking approach, and mapping the relationships between the various actors and elements of the PV Systems' life-cycle as accurately as possible, is that a designated entity (e.g., an agency delegated by the Ministry of Environment) would be able to focus its policies towards minimizing or maximizing the strength of these relationships as a function of well defined environmental KPIs, related to the PV end-of-life management, or, it could focus on the optimization of all sustainability dimensions (highlighted with blue frames below), in a controlled manner, and based on well defined priorities. This approach connects with the Case Study elaborated in the previous main section, concerning the optimal allocation of PV Panel Waste amounts to PV Recycling Centers in a way that total transport, logistics and emissions costs are minimized. The agency delegated to oversee the PV end-of-life affairs could decide, for example, to focus on three priorities, with quantified targets for each priority: (1) for year 2025 ensure that not more than x% of total PV Panel Waste sent to recycling is being disposed of as hazardous material at landfill sites; (2) emissions resulted from transport & logistics related to PV end-of-life are kept under a well defined target value; and (3) economic revenue is maximized. Then the causal loops information should support the agency to determine its strategy for 2025, based on its priorities (in this example). For example, the waste amounts sent to landfill could be reduced if the PV Recycling facilities improve their processing efficiencies, and this could be achieved through learning curves, but especially by providing incentives to PV Producers to design products which are easier to recycle and use cheaper, non-hazardous materials (NB. this would apply also for longer terms than just one year).

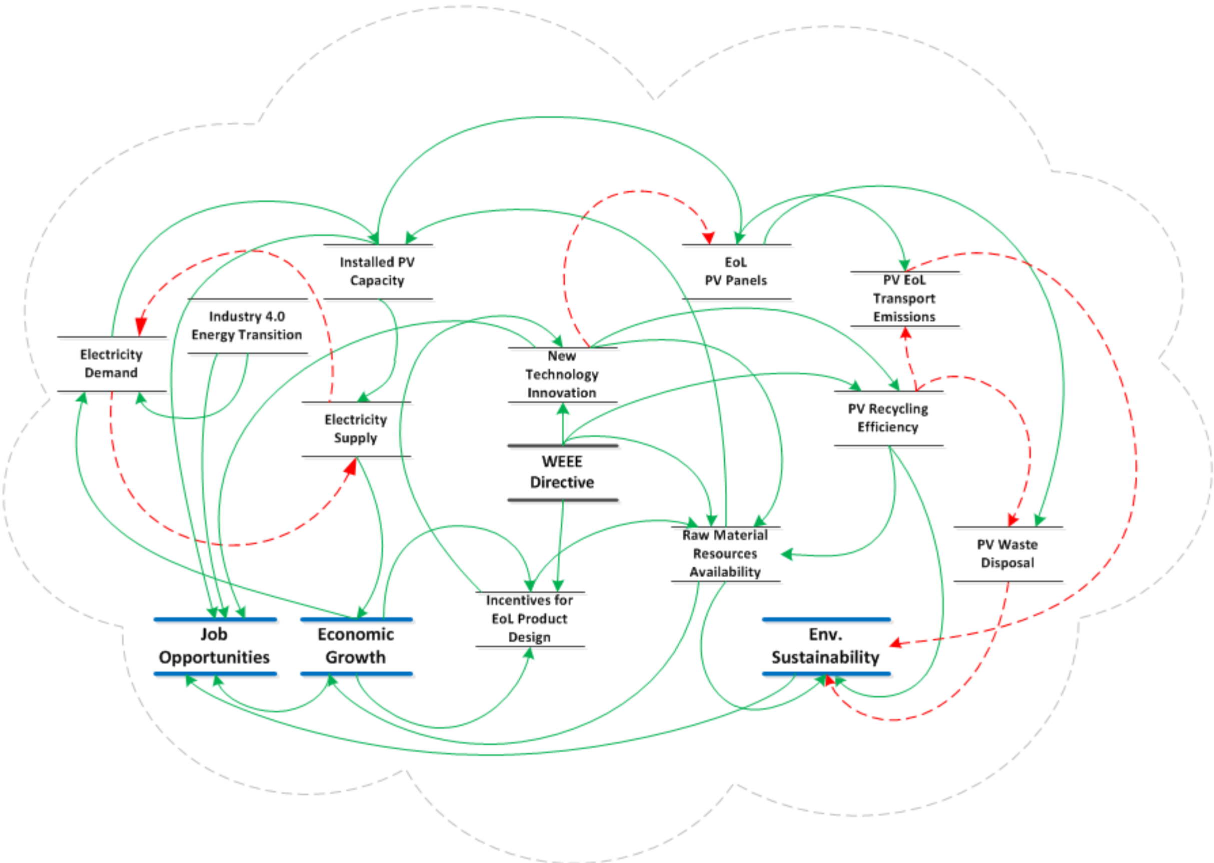

Figure 23 PV Systems Life Cycle Causal Loops (green-Positive Link, red-dashed-Negative Link)[18]

[18] Source: Roxana Predoiu

In addition to the above presented business and financing ideas, this thesis makes additional suggestions drawing on, and enhancing existing models, in an attempt to ensure that tri-dimensional sustainability will be achieved.

Undoubtedly, starting over the next few years, there will be gradually increasing PV Panel streams, that would need to be either repaired/reused, or treated for their end-of-life phase, and this would create excellent business opportunities for both the private or public sectors, interested to operate PV Recycling facilities. In order to safeguard both the economic and environmental sustainability this study recommends that a public, non-profit oriented agency, focused primarily on the environmental sustainability of the PV end-of-life is entrusted formally with the overall management process. Such an agency would be responsible to develop a solid network of information management, to collect data about the expected end-of-life PV Panels amounts, as well as all data about all materials recovered through recycling activities (amounts and types), as accurately and comprehensively as possible. This is an essential aspect, to obtain, and maintain reliable data about the amounts, the technology type, the geographical region (location), and the expected year of decommission for all PV Panels within a certain jurisdiction, probably the best approach is to manage this at national level, and/or at regional level (e.g., federal states, as in Germany, or United States).

This agency, a national, or regional hub, acting for the public interest, could develop various Private Public Partnerships (PPP) with the private sector. Firstly, this agency would be able to advise the private sector about PV end-of-live business opportunities, so that interested parties are well informed where and when will there be expected sufficient amount of PV Panel Waste, to warrant investment capitals, to erect and operate PV Recycling facilities. Moreover, this agency would be also in the position to prioritize environmental sustainability by assigning, based on a fair, performance benchmarked process, the amounts of PV Panel Waste to tendering PV Recycling facilities, while still ensuring that the PV Recycling ecosystem remains competitive, rewarding and self-improving. It would be necessary to define and be able to unbiasedly monitor and report on the environmental KPIs related to a PV Recycling facility operational performance: recycling efficiencies, efficient use of resources, proper treatment of hazardous materials, usage of green transport & logistics options, interest for developing improved recycling technologies, willingness to share information with the community, etc.. Once the KPIs and the measurements protocols are defined, a formally appointed entity, with the necessary credentials (e.g. TüV, Technischer Überwachungsverein) could take over the task to audit and report on these KPI values, at defined periods of time (e.g., annually). According to their website, the TüV Rheinland can support PV manufacturers and service providers by testing the quality of their PV modules, PV components, and PV systems. For example, the TÜV Rheinland's new Solar Energy Assessment Center in Köln has been in operation since June 2009, featuring optimized process flows and state-of-the-art testing and simulation facilities, the 2.000 m^2 center is one of the world's leading test laboratories **[51]**. They perform a series of services already (energy yield prognosis, PV system qualification and certification, PV inspections and PV acceptance, defect and damage assessments, PV system monitoring, project certification of large PV installations) and could probably easily take over the task of auditing the PV Recycling KPIs for such service providers.

As already established for the EU Member States with the Extended Producer Responsibility, it is a safe approach to require the PV Producers (a full 'Producer' definition from WEEE Directive has been provided some paragraphs above) to prefund the end-of-life phase management for all PV products they put on the market over every one calendar year. It is recommended that the fees are not simply calculated with a general formula which would render all PV Producers to pay the same fee amount, regardless of the involved PV technologies and any other factors. This would not stimulate the PV Producers and RnD organizations significantly to invest their efforts in designing new products, with new materials, and which would be cheaper and easier to be treated at their end-of-life, and it would likely become a 'tragedy-of-commons' story. Instead, once a new PV product is ready to enter a certain (national) market and undergoes the certification steps, there should be included a procedure to evaluate, with the best available recycling technology at the moment, the approximate costs for properly decommissioning the respective product, and consequently, to establish in a more accurate, and fair manner the recycling fee amount that the respective PV Producers would need to pay for their products.

The risk to the PV Producers is that, as recycling technologies also evolve and become more cost-effective and of high-value over time, by prefunding the PV Panels end-of-life, they may end up paying more than it would cost at the time when the end-of-life treatment would actually occur. The advantage of this approach is that any PV panels put on the market would have already been assigned clear responsibility for end-of-life phase, as the fees have been already paid, and these fees could grow up and be used over time (even before the end-of-life of the respective panels) in a fund managed by the central (public) agency.

Although currently there are not sufficient PV Panel Waste amounts to make it economically attractive for a large number of business initiatives to commence recycling facilities (with few exceptions, e.g., PV Cycle across Europe and First Solar at their own manufacturing locations), there are already significant amounts of PV Capacity installed over the world. Thus, for a country in this situation, the question is how to claim now the fees for the PV end-of-life for PV Panels which have been already commissioned over the last couple of decades, i.e. before any program to collect the end-of-life management fees would have been started. This would certainly require serious coordination efforts, and collaboration from the PV industry side, in order to proceed with data collection. The PV Producers which are still active could be asked to pay the end-of-life fees retroactively for PV Panels they put on the market in the previous years. For PV Producers which are not active anymore, or for which there is not enough legal support yet to hold them accountable for the PV end-of-life, other approaches would be necessary, and these will depend also on the involved amount of PV Panel Waste. Perhaps the collection and transport costs of some of these amount could be covered by the accumulating fund managed by the public agency, or other options may be better, depending on the local context (see further down the current national approaches, e.g. the UK). Furthermore, it is also essential to safeguard a level playing field for all energy producing systems in regards to implementing product end-of-life fees, in order to prevent competitive disadvantages between photovoltaics and other energy generation systems, and to encourage compliance.

While the PPP approach is becoming more and more common nowadays (also by virtue of SDG 17 = "*strengthen the means of implementation and revitalize the global partnership for sustainable development*") (**[44]**, **[46]**), and has been proved successful especially in long-term infrastructure projects, a country's national Ministry of Environment, representing the public interest, could benefit significantly from this type of partnership between its central, public agency and the private sector. Firstly, it would make use of already existing public infrastructure (e.g. collection and storage centers, or general waste processing facilities), and then also by benefiting from efficiency gains and expertise of the private sector, particularly in order to minimize any negative environmental impact, as a consequence of PV Recycling activities.

The PPP contracts could follow a relatively low complexity business model, with quick implementation, and the operations and maintenance risks would be transferred towards the private sector. As the private sector would need considerable investment capital to erect new PV Recycling facilities (Fthenakis and Choi **[12]** estimated in 2010 that USD 4 Million are expected as capital costs for a 20.000 Ton/Year PV Recycling facility, and such costs have been documented also elsewhere in literature, e.g., **[15]**, **[18]**, **[19]**), there is a certain amount of commercial risk transferred to them, for example, if there will not be enough PV Waste to keep all operational PV Recycling facilities busy at full capacity. This is another reason why it's critically important that PV Waste projections are as performed as accurately and comprehensively as possible.

If the commercial risk will be born by the PV Recycling companies, representing the private sector, this will translate into strong motivation to improve operational efficiency. To maximize both the economic profit and environmental safety, it would be also useful to find synergies, in terms of sharing existing infrastructure, new capital investments, logistics, etc., with the treatment and recycling of other e-waste streams which are expected to increase vigorously in the Industry 4.0 era, which will see a significant increase in the use of electronic and electric devices.

Concession could be one type of PPP contract that would work for PV Recycling. Concession contracts typically last long periods of time (e.g., 30 years), in some business areas this may be a disadvantage, as it may be difficult to anticipate how the business environment conditions will change, but in the case of PV Recycling, the forecasted amounts of PV Waste, and the increased reliance of the energy system on photovoltaics could alleviate the commercial risks considerably, provided, once more, that reliable forecasts are available, in regards to the expected streams of PV Panel Waste.

We know for sure that eventually all the installed PV Panels will reach their end-of-life phase and will have to be decommissioned. We just need to get a much more detailed perspective (compared with the IEA PVPS and IRENA 2016 projections **[10]**, which have a great merit in being the first ever performed global projections on PV Panel Waste) as to: when and where will this happen, what kind of PV Panels (technology) and what amounts, at a granularity level as fine as possible.

5.4 Current National Approaches For PV End-Of-Life Management

The information summarized in this chapter is based on the IEA PVPS and IRENA 2016 report on current national approaches for PV Waste management **[10]**, and on personal communication with persons listed in the main Methodology section (2).

5.4.1 Germany

Despite the fact that Germany only receives moderate solar irradiation compared to many other countries around the world (see **Figure 35** in Appendices section, based on **[47]**), the German PV market had started to grow early (compared to other countries), around 1990, mainly due to its feed in tariff support scheme, and Germany had been the world's leader concerning installed PV capacity until 2015 (for almost two decades). It is currently second only to China on the global perspective, and, at 40 GW installed PV by the end of 2015 remains, and projected to remain in the near future as well, the European leader for solar PV installations. The **Figure 24** displays projections up until 2050 for Germany's cumulative installed PV capacity (GW) and cumulative PV Panel Waste amounts (Million Ton).

The expected amounts of PV Panel Waste for Germany, for both the Regular Loss and Early Loss scenarios, between 2016 and 2050 are extracted in **Table 14.** By 2030 there are between 400,000 Ton and 1,000,000 Ton cumulative amounts of PV Panel Waste, and between 2,200,000 Ton and 2,600,000 Ton by 2040. By 2050 the values projected by IEA PVPS and IRENA unify for the two scenarios, at 4,300,000 Ton. Germany is therefore expected to become a major and early player on the PV Recycling markets over the next decades.

Table 14 GERMANY PV Panel Waste Projections 2016-2050 (extracted from [10])

YEAR	2016		2020		2030		2040		2050	
SCENARIO Regular and Early Loss	Regular Loss	Early Loss	Regular Loss	Early Loss	Regular Loss	Early Loss	Regular Loss	Early Loss	Regular Loss	Early Loss
Germany	3,500	70,000	20,000	200,000	400,000	1,000,000	2,200,000	2,600,000	4,300,000	4,300,000

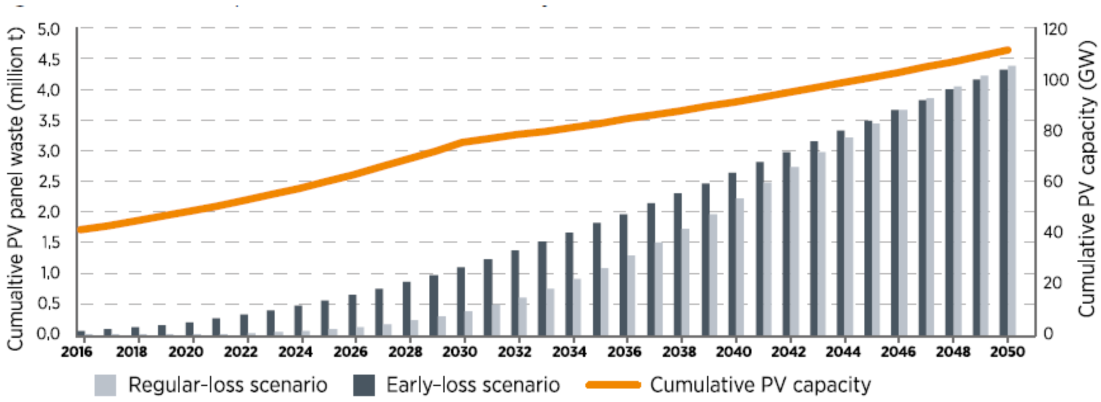

Figure 24 GERMANY - End-of-life PV Panel Waste And Cumulative PV Capacity 2016-2050[19]

The Germans have translated the recast WEEE Directive 2012/19/EU into national law in 2015, as a revision of the EEG (Elektroaltgerätegesetz or ElektroG). Stiftung Elektro-Altgeräte Register, or Stiftung EAR represents Germany's National Register for WEEE and it is empowered by the German Federal Environment Agency (Umweltbundesamt) to manage the country's e-waste streams. Stiftung EAR is an independent, non-profit organization, financed by fees and cost schemes supported by the Umweltbundesamt, the Nature Conservation, and Nuclear Safety. Its tasks as a e-waste Clearing House are as follows:

- To register Producers which place EEE products on the German market, and therefore will generate e-waste;
- To collect data on the amounts and types of e-waste generated from the German EEE consumers;
- To coordinate the public e-waste collection centers;
- To report annually on the flow of materials to the German Federal Environment Agency;
- To ensure that all registered Producers are treated fairly;
- To identify system cheaters and report them to the German Federal Environment Agency.

The EEE Producers (including PV Producers) and not the Stiftung EAR are responsible to monitor & coordinate the e-waste's physical collection, dismantling, recycling and final disposing activities.

[19] From [10], IEA PVPS and IRENA (2016)

Up until 2016 Germany has implemented the recast WEEE Directive in the form of a financial guarantee which (PV) Producers must provide for all the PV Panels they sell on the German market, in order to cover the future costs for collection, recovery and recycling of the respective PV Panels. The guarantee amount may be calculated with slightly different formulas, depending on the scheme that the PV Producer has adopted.

Whereas for PV Panels sold in B2B contracts the Stiftung EAR allows the producers and customers to agree between themselves how to fulfill the legal requirements for PV end-of-life, for B2C contracts, where the producers are part of a Joint-and-Several-Liability scheme, the financial guarantee is calculated with the following simplified formula:

$$\textit{PV EoL Guarantee Amount} = [\textit{PV Panel put on the Market (Ton)}] \times [\textit{presumed return rate}\ (\%)] \times [\textit{presumed disposal costs(EUR/Ton)}] \quad (1)$$

As of 2015, the Stiftung EAR had calculated an average cost of EUR 200 for one Ton of PV Pane disposal **[49]**.

Additionally, Germany has put in place a network of collection centers available for residential PV customers to dispose, free-of-charge, of their end-of-life PV Panels.

Voluntary approaches for the collection and end-of-life treatment of PV Panels, such as PV Cycle, have existed since before the recast of the WEEE Directive 2012/19/EU, and have now to become compliant with the new regulations.

PV Cycle was founded in 2007 and financed by the PV Industry, for the PV Industry, as a non-profit organization which offers collective and customized waste management services for companies and waste holders worldwide **[48]**. Only in Europe, as of 2016, PV Cycle was operating over 300 collection centers **[10]** and their 2016 Financial and Operating Report announced that PV Cycle processed over 15,000 Ton PV Panel Waste since 2010, and over 1,800 Ton in 2016, and it is considered the current world leader in the collection and treatment of PV Panels **[15]**.

Following the transposal of the recast WEEE Directive 2012/19/EU, there are two major financial approaches that Germany's government considers for the collection and end-of-life treatment of PV Panels: B2C and B2B transactions.

The ElektroG ensures the PV Producers (regardless of where in the world the PV Panels sold in Germany were manufactured) fulfill their obligations for the PV end-of-life when they sell PV Panels to private customers (residential rooftop PV), or customers with a similar demand profile (B2C). This approach follows the Joint-and-Several-Liability model and it's depicted in **Figure 25** below, where the central "Clearing House" is represented by Stiftung EAR, involving two levels for operation and financing activities. The German law requires PV

Producers who want to sell PV Panels in Germany (regardless of their origin) to register with a Clearing House and to agree on their responsibility to cover a share of the costs for both levels described below. The registered PV Producers receive a e-waste producer registration number which must be printed on their invoiced and labelled on their products sold in Germany.

- Level 1: ensures that collection and recycling for PV Panels put on the market before the PV-related extensions to the ElektroG. The costs are supported through a PAYG scheme, but the Producers are free to choose how they will fulfill this obligation: run an individual collection and recycling service, or join a collective service. Fulfilling Level 1 shared obligations ensures that older PV Panels (i.e. the first ones to reach end-of-life, before the law has changed) will be properly collected and recycled, which is particularly important for cases where the original PV Producers are not active on the German market anymore.
- Level 2: ensures that financing is available for end-of-life collection and treatment of PV Panels put on the market after the PV-related extensions to the ElektroG. The costs are supported through a PAYP scheme.

The B2B transactions involve larger amounts of PV Panels than typically sold for residential rooftop applications (e.g. large scale solar parks or much larger rooftop installations), and the German law is flexible in this case, as it allows the PV Producers to agree contractually with the final product owners on the most cost-effective option to deal with the PV end-of-life phase.

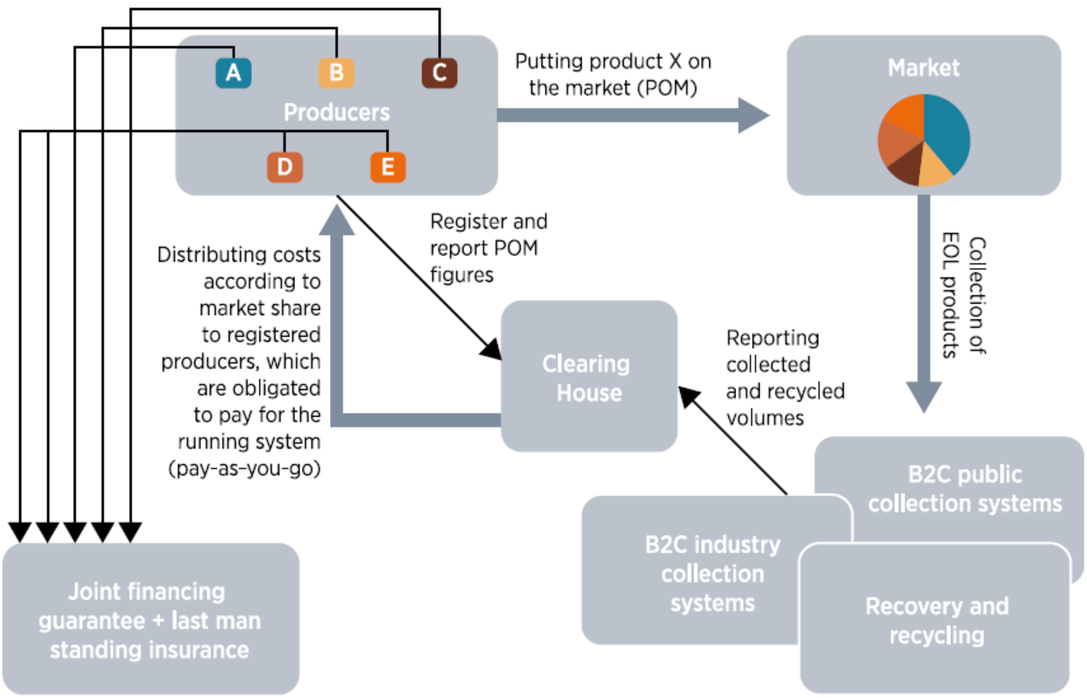

Figure 25 Collective EPR System For B2C PV Panels' End-Of-Life Management (from [10])

As Germany will soon start to be processing more of its end-o-life PV Panels it is expected that recycling costs will decline, due to the learning curve. Additionally, several RnD efforts are focused on improving the recycling technologies and rendering them more sustainable, in the long run.

One important statement made by Dr. Peter Pluschke, the Deputy Mayor in Charge of Environmental Issues for the City of Nüremberg, at the Vienna BRIDGE for Cities event in Sept. 2017 was that Bavaria, and in fact Germany overall, are aiming at steadily reducing the amounts of waste that is finally disposed of at landfills, e-waste included.

Germany's experience with PV Recycling activities could certainly help other countries to leapfrog, when their busy time to manage the PV Panels' end-of-life arrives.

5.4.2 United Kingdom

The UK's PV market is considered relatively young, but growing fast (three quarters of the cumulative PV capacity have been installed after the recast WEEE Directive was enacted in the UK, in 2014). Notably: there is currently a strong political focus for deploying building-integrated PV (BIPV). The **Table 15** and **Figure 26** below display the UK's projected cumulative PV capacity up until 2050, as well as expected streams of PV Panel Waste for both the Regular-, and Early-Loss Scenarios.

Table 15 UK Panel Waste Projections 2016-2050 (extracted from [10])

YEAR	2016		2020		2030		2040		2050	
SCENARIO Regular and Early Loss	Regular Loss	Early Loss	Regular Loss	Early Loss	Regular Loss	Early Loss	Regular Loss	Early Loss	Regular Loss	Early Loss
United Kingdom	250	2,500	650	15,000	30,000	200,000	350,000	600,000	1,000,000	1,500,000

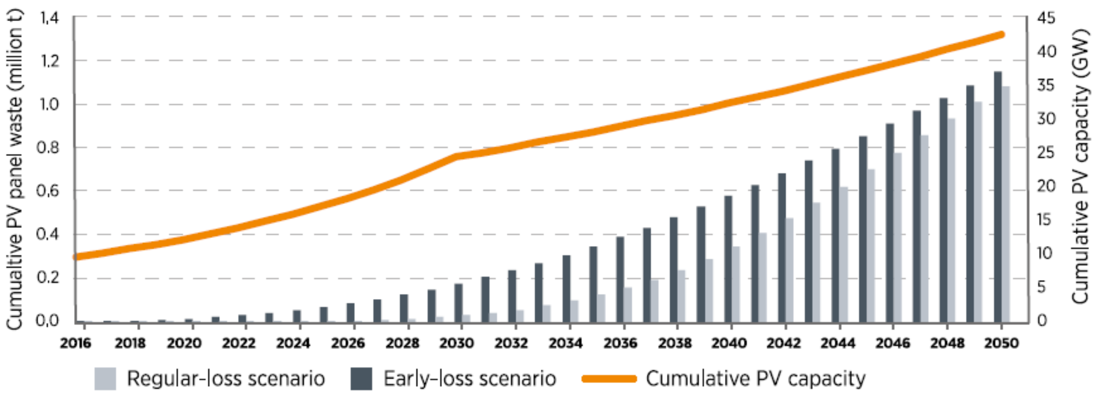

Figure 26 UK - End-of-life PV Panel Waste And Cumulative PV Capacity 2016-2050[20]

The fact, that most of the UK's PV capacity has been installed after the new WEEE Directive was transposed into law, simplifies somewhat the operational and financing processes

[20] From **[10]**, IEA PVPS and IRENA (2016)

related to PV end-of-life management. The UK has also adjusted the PV Producer definition, as follows: a UK PV manufacturer selling its own brand PV Panels, or, an importer of PV panels into the UK, or, an UK company selling under its own brand PV Panels manufactured or imported into the UK by another company.

After consultations with the PV Industry representatives, the UK has created a special WEEE category for PV Producers, a strategy expected to streamline and render the PV end-of-life activities efficient and sustainable. UK has currently a number of PV Producer compliance schemes which offer end-of-life management services for similar fees. The regulations concerning the financing for the PV end-of-life management by PV Producers can be summarized by transaction type, as follows:

- B2C: any PV producer which places a xx% PV Panels (by weight) as % of the total new installed PV market in any one year is required to finance the collection and recycling of (residential) of the same xx% of PV panels which reach end-of-live over the next year. A PV Producer does not pay for PV for end-of-life management during its first year of activity un the UK's PV market.
- B2B: the PV producers are required to finance the collection and recycling of non-household PV panels when these are being replaced by new ones.

5.4.3 Japan

Japan's market for installed PV capacity has seen a remarkable growth between especially 2012 and 2015 (from 6,7 GW to 34,3 GW) and it's expected to evolve at similar growth rate at least up until 2030 (see **Figure 27**). Main reasons for this development are: Japan's extensive RnD programmes, the introduction of a feed-in-tariff in 2012, as well as being home to a series of top global PV manufacturers (e.g., Kyocera, Sharp, Mitsubishi Electric, Mitsubishi Heavy, Panasonic).

The **Table 16** below provides detailed PV Panel Waste estimations for Japan, by IEA PVPS and IRENA (2016) for the Regular-Loss and Early-Loss Scenarios, and **Figure 28** displays a comparison between PV Panel Waste estimations by IEA PVPS & IRENA and Japan's Ministry of Economy, Trading and Industry (METI) and the Ministry of Environment (MOE), which differ based on different calculation methodology used by these organizations.

Japan's METI and MOE (2016) estimated that, assuming 25 years PV Panel lifetime and an initial failure of 0,3% panels during their first year of installation, a small amount of PV Panels will start reaching end-of-life before 2020 (approx. 2.800 Ton/Year in 2020). The figures are expected to increase gradually: approx. 9.500 Ton/Year for 2025, 29.000 Ton/Year for 2030, 61.000 Ton/Year for 2035 and a very large increase, up to 775.000 Ton/Year for 2039.

Table 16 JAPAN Panel Waste Projections 2016-2050 (extracted from [10])

YEAR	2016		2020		2030		2040		2050	
SCENARIO Regular and Early Loss	Regular Loss	Early Loss	Regular Loss	Early Loss	Regular Loss	Early Loss	Regular Loss	Early Loss	Regular Loss	Early Loss
ASIA										
Japan	7,000	35,000	15,000	100,000	200,000	1,000,000	1,800,000	3,500,000	6,500,000	7,600,000

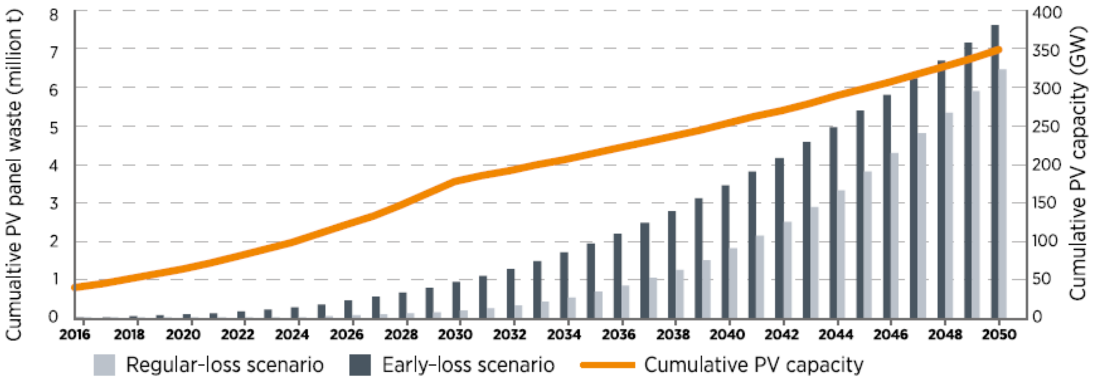

Figure 27 JAPAN - End-of-life PV Panel Waste And Cumulative PV Capacity 2016-2050[21]

Currently, Japan's regulatory framework for waste management does not foresee any specific handling of end-of-life PV Panels which fall under the general waste management procedures, i.e. the Waste Management and Public Cleansing Act., which provides rules for handling, e.g., the industrial waste, including final landfill disposal. According to current interpretations, it may be needed to recycle PV Panel Waste mixed with building material.

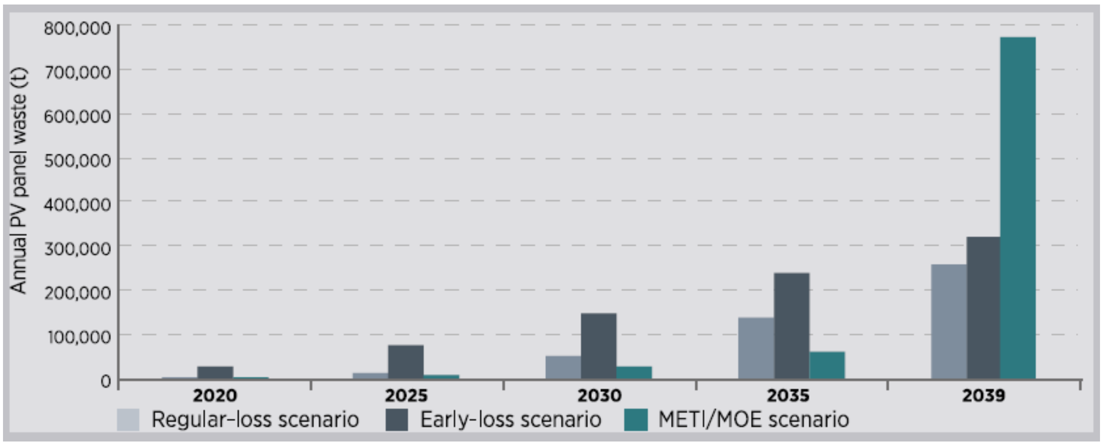

Figure 28 JAPAN - End-of-life PV Panel Waste-Projections Comparison (extracted from [10])

There have been several initiatives by METI & MOE since 2013 to evaluate how to handle the end-of-life phase for the technical equipment and materials used by the renewable energy industry (specifically the collection, dismantling, recycling activities), as well as encouraging RnD to concentrate their efforts also for designing sustainable products. These have resulted in a set of guidelines as of 2016 (the respective document

[21] From [10], IEA PVPS and IRENA (2016)

http://www.env.go.jp/press/files/jp/102441.pdf available on the Japanese government site, but only in Japanese).

5.4.4 The United States Of America

The US installed PV market has been growing steadily since the 2000's, it has reached 25 GW installed PV in 2015, and it currently represents the fourth largest global market for installed PV capacity, following China, Germany and Japan. The **Table 17** and **Figure 29** present, as for the other countries presented herein, the projected cumulative installed PV capacity for 2016-2050 and projected amounts of PV Panel Waste. The US are not looking at large cumulative amounts of PV Waste up until 2030 (between 170.000 Ton and 1.000.000 Ton), but are expected to become, by 2050, in both the Regular-Loss and Early-Loss Scenarios, the second largest producer of PV Panel Waste (after China), with 7.500.000 Ton and respectively 10.000.000 Ton.

Table 17 US Panel Waste Projections 2016-2050 (extracted from [10])

YEAR	2016		2020		2030		2040		2050	
SCENARIO Regular and Early Loss	Regular Loss	Early Loss	Regular Loss	Early Loss	Regular Loss	Early Loss	Regular Loss	Early Loss	Regular Loss	Early Loss
United States of America	6,500	24,000	13,000	85,000	170,000	1,000,000	1,700,000	4,000,000	7,500,000	10,000,000

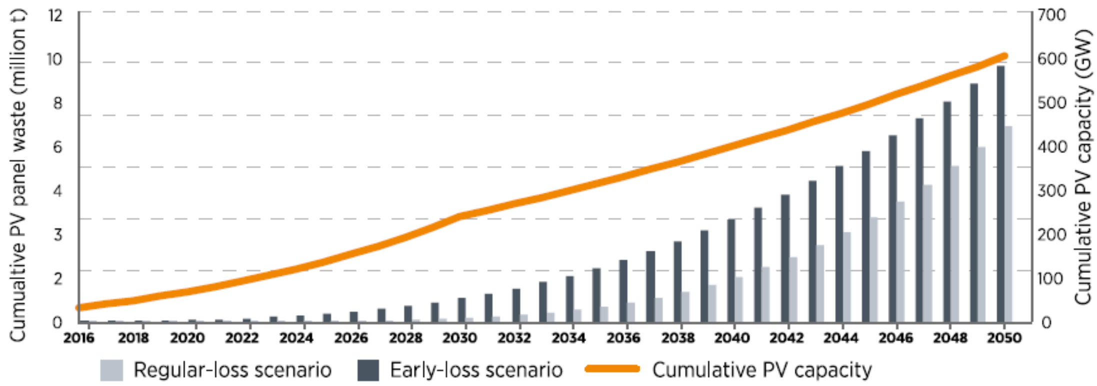

Figure 29 US - End-of-life PV Panel Waste And Cumulative PV Capacity 2016-2050[22]

Probably due to the low expected amounts of PV Panel Waste for the next two decades, there are currently no regulations specific for the PV end-of-life management, and the PV Panel waste is subject to the RCRA (the Resource Conservation and Recovery Act), which is the regulatory framework for the management of hazardous as well as non-hazardous solid waste.

End-of-life PV Panels are classified as hazardous waste if they fail the EPA TCLP test (Ag, Cd, Cu, Pb). Several states have regulations that go beyond RCRA. For example, California

[22] From **[10]**, IEA PVPS and IRENA (2016)

(CA) has additional threshold limits for hazardous materials classification and the CA Senate Bill 489 classifies end-of-life PV panels as Universal Waste (pending EPA approval) **[50]**.

Some of the common practices concerning the decommissioned PV Panels in US are:

- Sent to metal/electronics recyclers, e.g., Sun Power, Solar City, Sun Run;
- Sent to hazardous waste landfilling;
- Sent to regular landfilling;
- Sent to refurbishing those PV Panels still in good condition;
- Stockpiling in warehouses;
- Some PV Manufacturers have their own recycling policies for which they rely on a network of third-party recyclers;
- Other PV Manufacturers perform PV recycling activities at their own site, e.g., First Solar (in Ohio);

According to Mr. Fthenakis **[50]** the issue of (sustainable) PV Recycling activities is coming progressively under the rather.

5.4.5 China

Last, but certainly not least, China has become the world's leader in installed PV capacity in 2015, outranked Germany (world leader during the last two decades), by installing 15,2 GW of PV capacity during 2015, and 34,45 GW during 2016, by the end of which it reached 78 GW **[64]**. China's medium-term targets for cumulative PV deployment is 150 GW by 2020 (70 GW distributed PV and 80 GW of large-scale ground-mounted PV capacity). The IEA PVPS & IRENA (2016) long term projections for installed PV and PV Panel Waste are displayed in **Table 18** and **Figure 30**, announcing an almost exponential increase in PV Waste amounts between 2030 and 2050 (from between 200.000 Ton and 1.500.000 Ton in 2030, up to between 13.500.000 Ton and approx. 20.000.000 Ton in 2050). Moreover, China has been already for many years the world's leader in PV Panels manufacturing, in fact the 2015 top ten list of PV manufacturers contains, besides Trina Solar (top, with 4,55 GW PV Panel shipments in 2015) another six Chinese companies **[52]**.

As in the case of Japan, China's Institute for Electrical Engineering of the National Academy of Sciences (IEE) has made its own estimations for annual PV Panel Waste amounts, for a Business-as-Usual Scenario and a Better-Treatment Scenario (considering different operations and maintenance behaviours), both presented in **Figure 31**, in comparison with IEA PVPS and IRENA's Regular-Loss and Early-Loss Scenarios. Up until 2030, the projections from these two sources are similar, however, as of 2034, both IEE scenarios project considerably higher PV Panel Waste values than the IEA PVPS & IRENA, i.e. 900.000 Ton/Year and respectively 1.100.000 Ton/Year.

Table 18 CHINA Panel Waste Projections 2016-2050 (extracted from [10])

YEAR	2016		2020		2030		2040		2050	
SCENARIO Regular and Early Loss	Regular Loss	Early Loss	Regular Loss	Early Loss	Regular Loss	Early Loss	Regular Loss	Early Loss	Regular Loss	Early Loss
ASIA										
China	5,000	15,000	8,000	100,000	200,000	1,500,000	2,800,000	7,000,000	13,500,000	19,900,000

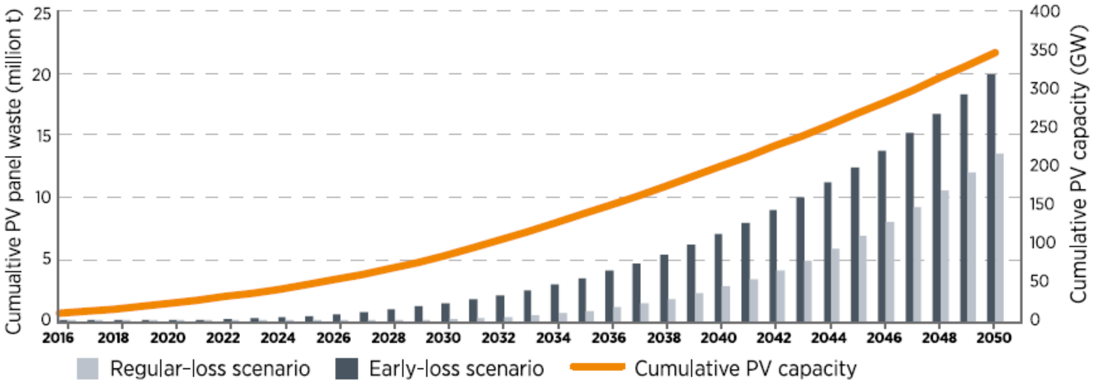

Figure 30 CHINA - End-of-life PV Panel Waste And Cumulative PV Capacity 2016-2050[23]

In regards to the Electric and Electronic Waste regulatory framework, the Chinese Ministry of Information Industry adopted the "Electronic Products Pollution Control Management Approach" in 2007, and later in the same year, the Chinese State Environmental Protection Administration issued the "Electronic Waste Pollution Prevention Management Measures", which ere followed in 2009, by the State Council's enacting of the "Waste Electrical and Electronic Product Recycling Management" regulations, implemented in 2011. The 2011 regulations foresee that Electric and Electronic Waste products shall be collected and recycled at through a centralized processing system **[41]**.

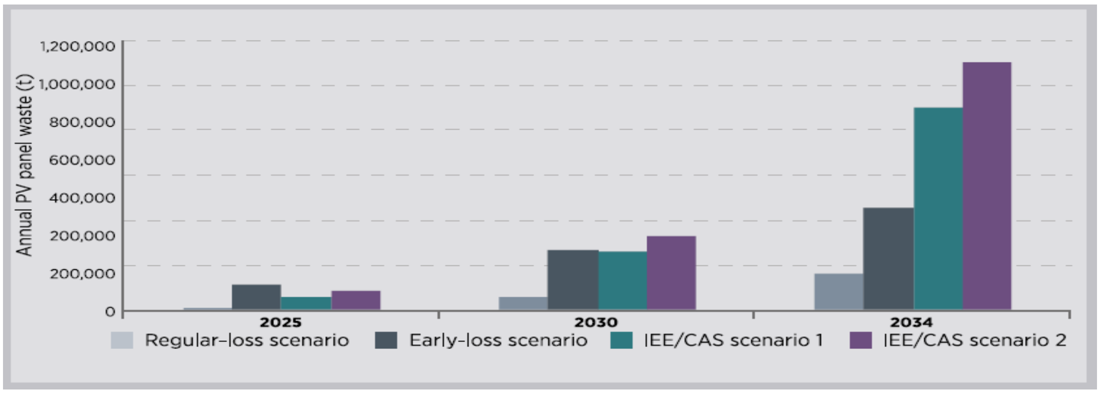

Figure 31 CHINA - End-of-life PV Panel Waste-Projections Comparison (extracted from [10])

The Producers can collect and recycle the Electric and Electronic Waste products by themselves, or delegate the task to sellers, after-sales service agencies, or third-party recycling service providers.

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[23] From **[10]**, IEA PVPS and IRENA (2016)

As the amounts of PV Panel Waste are currently very low, China does not have yet any specific regulations for managing the PV Panel end-of-life phase (PV Panels are not even included into the Electric and Electronic Waste products regulations at the present), nor do they have already a mature PV Panel recycling industry **[41]**. Nevertheless, research programmes have already started, for developing technology related recycling processes (low-cost, high-efficiency recycling for c-Si as well as thin-film PV Panels).

5.5 Industry 4.0 Emerging Paradigm

The global economy is currently on the brink of a new and promising Industrial Revolution, aka. Industry 4.0, which will depend on reliable, very fast wireless Internet connectivity, and will drive the development of the technical world in unprecedented manners, forming the Internet of Things (IoT). The IoT represents a virtually unlimited network of interconnected physical devices which are embedded with electronics, high performance software computing algorithms, and sensors continuously collecting and exchanging massive amounts of data. This technological transformation revolves around the triad of universal digitization, big data, and innovation, a paradigm which will trigger fundamental changes in manufacturing and work (collaboration) processes, and based on which computers and automation systems will come together in an entirely new fashion: remotely connected computer systems, equipped with machine learning algorithms able to collect and actively learn from data, will be able to monitor, take decisions, and control the robotics, rendering high quality production processes, with increased productivity. It is a change that comes with tremendous opportunities, and also with important challenges to overcome, in order to safeguard a smooth transition: new competencies (among which data technologies are particularly important) and management skills have to be quickly developed, cybersecurity issues need to be identified, regulated, and properly managed, public information and acceptance needs to be addressed, legislation and regulatory frameworks need to be enacted, triggering significant private and public investments in order to boost the digital innovation capacity, etc..

This is the current humankind's vision for the future smart economy and smart industry, which will bring on a new generation of products and services, across a wide gamut of activity sectors: manufacturing, electronics for automotive and aerospace, electronics for electric grid security and energy services, robotics, telecom equipment, business and professional software, laser and sensor technologies, construction, utilities, textile and craft industries, the health sector, mobility, research and development, etc., these are all sectors expected to be redefined to a large extent and to benefit from these digital opportunities.

Without doubt, also the sustainable management of PV end-of-life, still an emerging industry at global scale, will benefit from an early adoption of Industry 4.0 technological advances: more accurate and more complete PV Panel Waste projections leveraging on IoT connectivity and big data, increasing economic benefits during the PV Systems' lifetime by implementing predictive maintenance programs and improving PV System efficiency by adopting statistical performance monitoring, using blockchain technology to facilitate and accelerate online markets for trading secondary raw materials (recovered from PV Recycling) as well as repaired PV System components (sold as second hand), e-tagging of PV Waste (and e-waste in general) to ensure legal compliance and environmental sustainability, etc.

The following subsections before the thesis' conclusion propose and discuss some of the Industry 4.0 related concepts and how these could have a positive and practical impact on the sustainable management of the overall PV life cycle (including end-of-life), and therefore could contribute at least to the following UN SDGs: "9. Build resilient infrastructure, promote sustainable industrialization and foster innovation" and "12. Ensure sustainable consumption and production patterns".

5.6 Predictive PV Maintenance And Fault Detection

Availability, high efficiency, fault detection and extending the lifetime of installed PV Panels should be the first focus step when implementing the 3R (reduce- repair&reuse -recycle) paradigm. It has been long known that performing maintenance activities, at scheduled time intervals, to prevent (or limit) unexpected failures of system parts and equipment, can lead to better yields and service levels, and it could reduce Operations and Maintenance costs. However, taking these efforts to the next level, based on (collected) data driven approach, and actually *predicting* where and when such failures might occur, and taking corrective actions, can positively impact revenues and asset reliability (particularly important for critical equipment). This would result in even more important cost savings, by keeping the assets performing optimally for their entire lifetime. An increasing number of IoT projects, including the PV industry, relying on sensor-based data collection, computing systems, sophisticated machine learning algorithms[24] and data visualization frameworks, are focused on such initiatives today, aiming to support the optimization of maintenance schedules and resource usage by predicting equipment failure.

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[24] "*Evolved from the study of pattern recognition and computational learning theory in artificial intelligence,machine learning explores the study and construction of algorithms that can learn from and make predictions on data – such algorithms overcome following strictly static program instructions by making data-driven predictions or decisions through building a model from sample inputs. Machine learning is closely related to (and often overlaps with) computational statistics, which also focuses on prediction-making through the use of computers. It has strong ties to mathematical optimization, which delivers methods, theory and application domains to the field. Machine learning is sometimes conflated with data mining, where the latter subfield focuses more on exploratory data analysis and is known as unsupervised learning. Machine learning can also be unsupervised and be used to learn and establish baseline behavioral profiles for various entities and then used to find meaningful anomalies*" (wikipedia.org)

In Italy, for example, the predictive maintenance concept has been recently developed after Stern Energy[25] has been called in several times to resolve unforeseen severe technical problems with PV systems which were identified by the system owners only at a late stage, after the energy production had been already seriously affected.. The added O&M annual expense for highly specialized predictive maintenance was estimated between EUR 2.000 and EUR 4.000 /MW (per year), and this approach is considered to eventually become much more cost effective than providing repair services *after* the faults and outages have occurred already. Stern Energy will be presenting its predictive maintenance system alongside Suncycle at the upcoming Solar Asset Management Europe conference in Milano/Italy, on November 9-10, 2017. Their service offering includes expert maintenance services for solar inverters as well as analyses of panel quality, to reveal early signs of problems such as solar cell potential induced degradation or PID, which can lead to power losses of up to 50% and may be difficult to spot at very early stages within traditional operations and maintenance schedules **[53]**.

Predictive maintenance differs from classical preventive maintenance as it is not based on a preset schedule depending on average or system expected life statistics (e.g. change the engine oil after every 5.000 working hours), but it rather takes the “system pulse” (online periodic or continuous system monitoring) and it detects the system’s current need for maintenance based on certain measurements which help detecting the onset of system degradation (i.e. a lower functional state). These allow the causal stressors to be eliminated or controlled before any significant deterioration happens in the system (or system component). The data collected by such measurements is used to automatically determine the current and future functional capability of the in-service equipment, and when any maintenance should be performed.

Some advantages (+) and disadvantages (-) of predictive maintenance based on **[54]**:

- (+) A well-planned predictive maintenance program could eliminate disastrous equipment failures;
- (+) Allows for scheduling maintenance when really needed, and minimizing, or completely avoiding overtime costs;
- (+) Minimizes the stocking of system spare parts and order them only when necessary to support downstream maintenance needs;
- (+) Allows for cost savings in excess of 30% to 40%, according to past studies and surveys;
- (+) Attractive Key Indicator values: Return on Investment: 10 times; maintenance cost reductions: 25% to 30%; elimination of breakdowns: 70% to 75%; reduction of

[25] Stern Energy = Italian Operations and Maintenance service provider, managing a portfolio of 140 MW solar PV installations across sixty sites in Italy **[53]**

downtime: 35% to 45%; increase in production: 20% to 25%; estimated 8% to 12% cost savings over preventive maintenance program;

- (-) Increased investments in diagnostic equipment and software systems;
- (-) Increased investment in staff training;
- (-) Savings' potential not always easy to be seen, or understood by investors

IBM's Watson IoT is one of the technical solutions currently available to assist (also) PV electricity generation companies with implementing predictive maintenance and resource optimization programs (PMO), by collecting (customer's system) data and using advanced analytics **[55]**. According to the IBM white paper, these predictive models enable the manufacturing and maintenance personnel to:

- "*Quickly assess performance of critical equipment to help plan and prioritize maintenance schedules:*
- *Determine which equipment is being over-, under- or well-maintained and use prescriptive analysis to optimize maintenance practice;*
- *Identify operational factors that positively and negatively affect equipment performance and use this information to guide maintenance strategy and procedures;*
- *Determine which factors are most influential in affecting equipment performance;*
- *Examine the detailed performance aspects of equipment, including attributes, risk factors, maintenance logs, and predicted time to failure, and use this insight to prescribe equipment-specific or equipment-class maintenance strategies*."

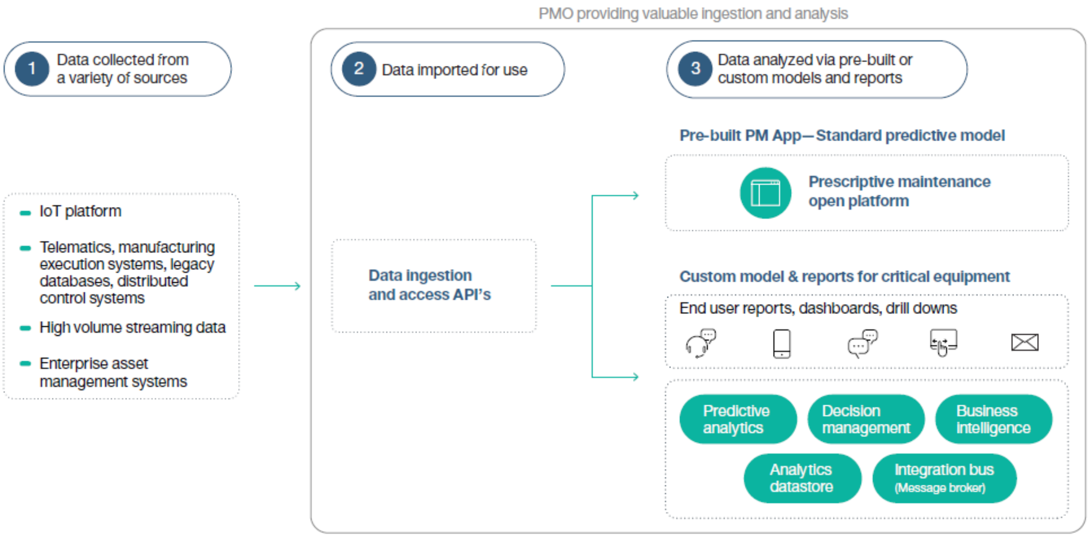

Figure 32 IBM Watson IoT: Predictive Maintenance and Optimization (from [55])

The IEA PVPS Task 13 focuses on improving the PV Systems' reliability by collecting, analyzing and disseminating information on their technical performance and failures. One of their most recent studies (**[56]**) focuses on practical methods for improving the PV Systems efficiency through advanced statistical analysis, which could enable quicker and more exact system alerts (e.g. alerts on low-producing PV arrays), and could facilitate system performance monitoring. These methods are technology independent, applicable to grid-level integration of distributed energy system, suitable for large PV plants but also for commercial, small industrial and residential systems. The latter ones are usually not subjected by their owners to professional monitoring and maintenance operations (e.g., rooftop installations which become more and more frequent in many countries around the world). Since many of these residential PV systems are grid connected, it is essential for grid operators and energy utility companies to have confidence that the overall system stability and accuracy (meet demand with supply) are not negatively impacted (within defined limits) by these systems contributing electricity to the grid. Some options to mitigate the challenges triggered by grid integration of such distributed energy generation systems are as follows: providing the grid operator with better forecast electricity generation from PV residential systems, increasing the system availability, and lowering the forced outage rate (treating these residential PV systems as virtual multi-megawatt power plant).

Smart meters and new inverter technologies already allow system monitoring and device communication. Simple metrics are currently provided to support the system operator to evaluate the "system health", e.g., inverter comparison (if more than one inverter exists), and performance ratio calculation (when solar irradiance data are available). IEA PVPS present four practical cases which can contribute to increasing PV system efficiency.

The first system was developed in Australia for residential PV systems by Solar Analytics Pty. In Australia, 98% of the approx. 1,6 million installed solar systems are residential, or commercial under 10 KWp. Solar irradiation data are available free of charge from the Australian government. The system consists of a simple energy meter, installed onto the electrical power-distribution box that collects data. Generated electricity data is analyzed with statistical methods and compared with the expected electricity generation profile, determined based on the available solar irradiation data and the system configuration. The system owner has access to real-time electricity generation data and a fault diagnosis, which identifies issues and suggests the checks when the system underperforms.

The second system (from the Israeli company M.G.Lightning Ltd) aggregates a number of small residential PV systems into a virtual neighborhood power plant, for which it uses machine learning algorithms to predict the next day's electricity generation on hourly basis. This system requires only inverter data feed to the system server, no current day irradiation data or system configuration data are needed. The algorithms work only with electricity generation data obtained from the inverter and meteorological predictions extracted from commercially available meteorological servers. The machine learning algorithms are applied on previous day weather history, as opposed to weather forecast information, and produce an immediate indication of system health, simply rated (qualitatively, from A to F), and allowing even the owners of small residential PV systems to easily recognize when their system underperforms, and call the service.

The third system (again from the Israeli company M.G.Lightning Ltd) uses more advanced machine learning algorithms for the prediction of system faults. It requires only data from the inverter loggers and access to historical meteorological data, extracted from commercially available (inexpensive) meteorological servers. As in the previous case, no irradiation data or system configuration data are required. Clustering predictive analytics methods are applied to predict future faults that will affect the PV system's electricity generation. This system has managed so far to predict future electricity generation losses due to faults, and it's currently work-in-progress to manage also the classification of a specific fault that will occur. This will support the system owner to take proactive measures and minimize revenues losses as well as inflicting issues upon the electric grid.

The fourth system (from Sandia National Laboratories of the United States) tackles a promising application of artificial neural networks, it's currently work-in-progress and has been tested with good results (test systems only), but it requires further efforts, to be tested with data from various locations, during different seasons (i.e., diverse solar irradiation and weather conditions), and to be trained for the detection of a larger spectrum of fault conditions. The algorithms learn the system behavior from the available data inputs, then the learned behavior is compared with real-time system parameters. It is expected to facilitate fault detection considerably faster than current methods, e.g., the performance ratio, the inverter comparison or the power performance index.

These four case studies (from independent research centers, and largely distributed geographically) indicate that PV Systems' monitoring starts moving from a sensor-based approach to one based on statistical algorithms, performed on system electricity generation data (available from invertors) and inexpensive weather data. There is a growing number of small PV (residential) systems which provide electricity to the grid, and which typically cannot afford expensive, high-efficiency monitoring systems on their own. The benefits of using (big) data collection coupled with statistical analysis, requires only computation systems, and could potentially reduce the O&M costs, improve the system performance and overall reliability (including the grid operator perspective), and simultaneously extend the system lifetime, due to timely fault forecasting.

5.7 Blockchain-Based PV Secondary Markets

Following a sustainable approach for the PV Panels life cycle, the Repair/Reuse is the preferred option, prior to commencing any end-of-life recycling activities (discussed in previous sections). Repaired PV Panels may be sold for special projects, or, rebranded & relabeled, and sold directly on a second hand market, There are currently a few modest initiatives for online selling of refurbished PV Panels and other PV Systems components (e.g., www.pvxchange.com, www.secondsol.de, www.ebay.com/b/Solar-Panels), but currently it does not seem to be a more general online market, easier to find or to deal with, as people may be typically reluctant to conclude such transactions: unsure about payment security, or the quality and guarantee provided for the marketed second hand products, etc. One option proposed by this thesis in order to facilitate and accelerate the development of such online markets, and render them more direct and more secure for all involved parties, is to use blockchain technology, for selling/ buying second hand PV components, as well as recovered raw materials (traded as commodities).

Blockchain (a decentralized, fully traceable, secure-by-design, continuously growing software ledger of escrow-like records, aka. 'blocks' of permanent and tamper-proof information, which are 'chained' to each other, and secured by using cryptography, and which do not require intermediaries to safely conclude peer-to-peer transactions), although not new[26], it is still considered an emerging technology, growing rapidly across a wide variety of economy sectors, and replacing the need for third-party institutions to provide the necessary trust for financial and contract transactions.

A 2015 World Economic Forum survey (based on an international community of over 800 executives and experts from the information and communications technology sector) has estimated that by 2023 national governments will have implemented tax collection by using blockchain technology (73% respondents) and by 2025 about 10% of the global gross domestic product (GDP) will be stored in, and managed with blockchain technology (58% respondents) **[58].** It is expected that the global economic and monetary paradigms will be significantly reshaped by new systems anchored in "blockchain" technologies, which will render traditional pricing mechanisms and exchange systems less necessary and less relevant. Blockchain is gaining traction rapidly, and the world, and the society are re-defining themselves around revolutionary concepts. And there are certainly challenges that blockchain technology still needs to overcome, but here are some of its anticipated positive impacts are:

- Increased delivery of financial services at affordable costs to sections of disadvantaged and low-income segments of society, as financial services on the blockchain gain critical mass (financial inclusion);
- Disintermediation of financial institutions, as new services and value exchanges (including commodity markets) are created directly on the blockchain;

[26] For a comprehensive blockchain overview and timeline please see also:
en.wikipedia.org/wiki/Blockchain
www.thebalance.com/blockchain-and-supply-chain-sustainability-4129740
www.greenbiz.com/article/what-blockchain-can-do-environment
www.letstalkpayments.com/3-companies-leading-the-blockchain-as-a-service-baas-revolution

- Exponential growth in tradable assets, through the diversification of value exchange that can be hosted on the blockchain;
- Better property records in emerging markets, and the ability to manage everything a tradable asset;
- Contracts and legal services increasingly managed through blockchain, to be used as unbreakable escrow or "smart contracts", which are code-based programmable contracts, without the need for intermediaries to process the payouts between two parties once a set of defined criteria have been met. Such contracts are secured in the blockchain as "self-executing contractual states", and eliminate the risk that others will not fulfill their commitments;
- Proactive supply chain sustainability (including raw materials trading and second hand PV components, which are relevant herein) will allow the early detection of dishonest suppliers and counterfeit products;
- Lower costs (overhead costs eliminated), faster transactions and increased transparency, as the blockchain is essentially a distributed open global ledger storing all transactions, in a tamper-proof manner **[59]**;

Blockchain is spreading rapidly in the world, including the commodity trading sector (raw materials) and this thesis considers that all actors (regardless if private or corporate, small or large) involved the emerging industry of PV repair/reuse and recycle could benefit significantly from adopting blockchain technology to facilitate the transactions inherent to these business activities, in a secure, fully traceable manner, and involving less bureaucracy (overhead costs), as well as diminished commercial risk for involved parties.

5.8 E-Waste Tagging, Mobile PV Recycling, PV Data Collection

The global challenges related to E-waste management, lack of transparency and abuses have been extensively documented in countless journal articles, on government and NGOs websites, etc. The WEEE Directive has been born out of necessity to handle the exponentially growing amounts of e-waste in EU countries in a sustainable manner, particularly from environmental perspective (Europe alone produces over 9 Million Ton e-waste annually **[60]**). But not all countries around the world, and especially not many developing and less-developed countries, have already enacted and enforced the appropriate legislation and regulations to protect their environment from becoming a dumping site for e-waste. Even in Europe it has been estimated that, despite of strong WEEE legislation already in place, less than 40% of the generated e-waste is treated according to the defined legal and environmental requirements. This process will take time, however, there is hope that a growing number of e-waste tagging initiatives, showing promising results already, will soon become largely adopted and will support with better accountability (in conjunction with Extended Producer Responsibility) for any e-waste generated amounts (PV Panel Waste included).

By using radio-frequency (RFID) tagging or image recognition, the EU-funded project WEEE TRACE ('Full Traceability of the Management of WEEE') aims at harnessing comprehensive information by using inexpensive communication technologies in the fight against illegal exportation and substandard treatment of WEEE, with an ultimate goal to ensure e-waste management full traceability, increase collection rates, reduce the illegal flows and ensure proper end-of-life treatment **[60]**. Similarly, the Basel Action Network have been implementing and frequently reporting on their e-Trash Transparency Project **[62]** which uses small GPS-based tracking devices to collect data on the trajectories of e-waste items, and also the Electronics Recyclers International (ERI) have launched in 2013 the MyTrackTech, an innovative software that enables organizations which recycle their e-waste through ERI to have real time access to all recycling data in real time and fully customizes their recycling experience **[61]**.

This thesis considers that e-waste (PV Waste included) tagging by ICT devices, combined with blockchain technology for transactions monitoring and end-to-end process transparency, as discussed in a previous section, have the potential to improve significantly the global e-waste management. Once such solutions have started to mature and gain confidence in their learning curves and achieve cost reductions, they could be deployed, at reasonable costs, also in less developed countries.

The LP model presented in this thesis addressed the optimization of total transport and logistics costs for PV Recycling activities at dedicated recycling facilities, involving collection at central take-back-centers and (potential) extra travel distances to the recycling facilities. This solution would work optimally in case of large amounts of PV Panel Waste typically produced by a PV solar plant, or by residential PV installations located relatively close to any of the collection centers. There are, however, many cases (depending on country, or region) where residential PV installations may be located in more remote, or more dispersed locations, which would significantly increase total logistics costs per Ton of PV Panel Waste sent to recycling. For such cases (but not limited to), PV Mobile Recycling solutions may be much more cost effective.

PV Cycle have been involved in a joint project PV MOREDE (Photovoltaic Panels Mobile Recycling Device) since 2013. The goal is: "*the development and industrialization of a mobile recycling device for discarded PV modules at the end of their life cycle. The project foresees the market entry of an innovative process for on-site PV panel recycling and will develop at least one PV Morede device for each Germany, Spain, France and Italy by 2016, with a total treatment capacity of 270,000 panels or the recovery of up to 4,735 tons of glass, 669 tons of aluminum and 7.6 tons of copper. Compared with other industrial waste systems, PV Morede is able to treat PV modules directly where they are installed, allowing a cost-*

effective and easily accessible waste treatment for small quantities of PV panels. Treatment costs are expected to decrease by up to 40% per treated PV panel tonne. *PV Morede is particularly suitable for treating first generation photovoltaic panels and allows the recovery of several types of important waste products, such as glass, photosensitive metallic material or "light compound*"[27].

A couple of many other encouraging initiatives, which could positively shape the sustainability of the entire PV Systems' life cycle (end-of-life management included), are: drone based solar panel inspections (cost effective for medium-large solar power plants)[28] and ElectriCChain[29], which is a blockchain-based platform whose mission statement is: "*ElectriCChain is: 7 million global solar facilities watching the skies 24/7 for Climate Data, Micro-Climate monitoring, Pollution tracking and Academic purposes. ElectriCChain does: dynamic posting of live solar production data to a single blockchain as Standard Communications Protocol for the Solar Industry. ElectriCChain helps: government institutions, the solar industry and prosumers in order to deliver cheap and clean solar energy for future generations*".

This thesis considers that such applications will contribute to elevate operational efficiencies (e.g. for being able to perform certain maintenance steps with drone support much faster than by deploying human workforce on the ground, especially for large PV installations) and will see increases in the scope of work as synergies will be developed across industry sectors, and (drone) technology cost reductions will be achieved, rendering the technology commercially available and competitive. Initiatives like ElectriCChain could be pivotal for optimizing PV data collection, which, combined with smart data analytics algorithms could contribute to improving the PV Panel Waste projections, over short-, mid-, and long-term time scale. Consequently, improved PV Panel Waste projections will foster reliability in the new business environment for managing the PV end-of-life.

6 Conclusions And Next Steps

Based on literature review, as PV capacity installed globally keeps growing, the business case for a sustainable management of PV Systems' end-of-life will offer attractive economic opportunities. As early as 2030, the PV Panel Waste could become a goldmine, there will be important amounts of PV Panel Waste available for recycling processes, for recovering considerable economic value, and fostering a circular economy.

[27] European Innovation Project For On-Site Recyclig:
www.pvcycle.org/press/mobile-recycling-unit-for-pv-end-of-life-treatment/

[28] www.waypoint.sensefly.com/conducting-a-solar-panel-inspection-with-an-ebee-drone

[29] www.electricchain.org

Starting with a comprehensive literature review, this thesis has proposed and discussed several options which have the potential to support a sustainable ecosystem for the emerging PV end-of-life management.

The following main conclusions and methodology guidelines can be extracted from the work and analysis done for this thesis:

- The 3R must be adopted as paradigm also for the sustainable management of PV end-of-life phase. (**Reduce-Repair-Recycle**);
- It is important to ensure that (also) PV Products are designed in order to reduce the economic and environmental costs, and to improve the processing efficiencies related to the end-of-life phase management. Legislation and regulatory frameworks will be needed in order to channel the RnD and manufacturing efforts towards better recyclability. (**Create Legislative & Regulatory Frameworks to foster Product Recyclability**);
- Based on literature review: most countries have just started, or not even started to define and implement regulatory and compliance schemes to deal with the PV end-of-life management. A few countries (e.g., Germany) which will start earlier with PV Recycling activities, have already implemented regulations and started operational recycling processes.
  Their experience could help other countries to leapfrog through their learning curves. (**Share the knowledge and reuse the lessons learned**);
- There is a collection of already explored / tested PV end-of-life management business models, financing and policy options, as reviewed in the main Discussion section. This thesis considers these models having a common denominator (detailed in the Discussion section), but in order to be successful they may also need to be adapted to country specific conditions, i.e. depending on maturity of policies and institutions, infrastructure, civic commitment to implementing the SDGs, etc. (**There is no universal recipe but local adaptations based on a common denominator**);
- PV end-of-life management policies and practices need to be part of a wide spectrum of cross-cutting instruments to support a sustainable PV life cycle approach. Adapted for specific national conditions, and depending on national maturity of the PV sector, the enabling framework should facilitate the development of institutional, legislative, technological, financing, logistics, and human capacities, by following an integrative system approach where all stakeholders with their interactions and linkages are well understood, and can be modelled/controlled based on defined and quantifiable sustainability goals. (**Systems Thinking approach works better**);
- Identify, grow, and exploit synergies, e.g., the larger global case of e-waste. Implementing common policies, sharing infrastructure, taking advantage of the overall business case's amplitude to push forward a practical agenda for legislative policies and regulatory actions, as well as financing mechanisms. Synergies with the overall Energy

Transition process are also desired to be identified and exploited. (**Develop Synergies to speed up the e-Waste management process and reduce the costs**);

- Adopt Extended Producer Responsibility (EPR), drawing on the European Union model and experience with the recast WEEE Directive 2012, in order to safeguard the environment, to motivate the PV Producers to design their products with respect to the end-of-life phase (cheaper, more common, non-hazardous materials, easier and more efficient to recycle), unburden the end-customers from paying additional fees for PV end-of-life treatment, and prevent system cheaters. As with the WEEE Directive specific targets, one major goal is to increase the e-waste collection rates (PV Panel Waste included), and depending on the country's specifics, this could be accomplished by implementing EPR, and/or incentivizing the end-customers (or penalizing the cheaters) to diligently take their e-waste to appropriate collection points (**Implement EPR and improve e-Waste Collection Rates**);
- Mitigate commercial risks and contribute to logistics optimizations by expanding PV Systems performance monitoring, implementing cost-effective predictive maintenance programs, and continuously improving the accuracy and completeness of data collection, and reporting for expected PV Panel Waste streams by (at least) four dimensions: PV Panel technology, expected PV Waste amount, geographical location of PV Panel Waste origin, year of expected end-of-life (decommissioning). (**Improve PV System Monitoring, Maintenance and Data Collection & Reporting Systems**);
- Research and Development, innovations, Industry 4.0 paradigm, knowledge sharing platforms, education and training, continuous feedback loops between the PV Recycling, PV Manufacturing industries, municipalities and environmental agencies / organizations tasked with the fulfillment of the UNs Sustainable Development Goals, are all pivotal to fostering a sustainable PV end-of-life management. (**Leverage globally on technological advances and focus on the fulfillment of the SDGs**);

This thesis has proposed a linear optimization model which could support an agency empowered by a national government to coordinate the sustainability aspects related to PV Panel Waste end-of-life management (likely coupled with the general e-waste management process), and to minimize the overall transport and logistics costs associated with PV Panels end-of-life (e.g., Germany's Stiftung EAR).

Regarding the way forward, this model could be further developed, and several options are possible, and could be useful. A Goal Programming (optimization) model could be developed to support the above mentioned agency to implement and prioritize certain environmental KPIs related to the environmental impacts due to PV Recycling business activities. This approach would fine-tune the sustainability of the overall business model by allowing the (central, non-profit) agency to focus on environmental sustainability with higher priority, while still ensuring that economic growth is achieved, on a fair basis (e.g., not a monopoly based system), and the PV Recycling business units will obtain satisfying revenues.

Another Goal Programming model could be developed to assist PV System owners in a decision making process as to when is the right time to decommission their existing PV Panels and invest in new PV Systems. Even if predictive maintenance has been diligently implemented, and the existing PV Systems continue to perform optimally through their entire lifetime, it is estimated that overall system performance degrades steadily, mainly due to performance degradation of the PV cells (0.5% per year of operations, as per Fechner, H., TU Wien Photovoltaics lecture, 2016). Besides, new technologies have been occurring, with improved efficiencies, and lowering costs. Through the use of predictive analytics, feeding on comprehensive IoT sensor-based data collection, a goal programming model could optimize the decision as to when it is worth (both economically and from environmental perspective) to replace older PV Panels with new ones. It would be recommended to double-check the results, e.g., by audit from an external party, in order to ensure that PV system owners are not tempted to dispose of older systems ahead of time, simply because it would be more profitable for them, in terms of economic profits. It would take a series of input parameters which need to be accurate: new investment costs, existence (or cessation) of any FiT support schemes, available financing schemes and costs for PV System dismantling, collection, transport, costs for the recovery and recycling of the old PV Panels, any gate fees for landfill sites, any environmental taxes or incentives (e.g. Carbon Tax, or credits for environmental sustainability, if regulated), costs for transporting and installing a new system, etc..

PV Panel Waste projections could also be improved over short- to large time scale, by leveraging on the quickly expanding deployment of IoT applications (e.g., smart grids, smart meters) which would allow the aforementioned central agency to share and aggregate data already collected by grid operators in order to apply predictive analytics algorithms, and forecast with greater precision the time, place, and amount of expected decommissioning phase for installed PV Panels. Where this is not possible, or not cost-effective, other methods need to be developed and applied for complementing data collection and forecasted streams of PV Panel Waste.

Further studies are needed to develop strategies for PV end-of-life management particularly for developing and less-developed countries where solar power capacity has already started to be installed and will grow over the next years, as part of their own commitment to Energy Transition and the SDGs (e.g., in African countries, or small Pacific islands). Although it may take several years before significant amounts of PV Panel Waste may be generated, it is important to analyze in a timely manner what are the practical options for such countries to implement sustainable PV end-of-life processes, and to prepare the environment, e.g., by building local technical capacity through trainings, and by benefiting from existing local innovations. For example, Kenya's M-Pesa mobile money accounts could be combined with bureaucracy-free, secure, transparent and easily accessible blockchain applications to incentivize private persons to contribute to improving the PV Panel Waste (and e-waste in general) collection rates. As described in this thesis' Discussion, there is a common denominator related to PV end-of-life processes, but the practical methods and business models for implementing these may vary between countries, or regions of the world, depending on available financial support, maturity of local environmental institutions and policies, as well as public compliance with such policies.

This thesis' work may be valuable to the following (but not limited to): municipalities which are looking forward to aligning their activities with the UN SDGs Agenda (goals and targets); PV manufacturers which need to catch up with the latest trends (economic and regulatory) concerning the PV end-of-life management, businesses interested to start operating PV Recycling facilities, environmental agencies which could adopt linear programming models to manage their environmental KPIs in optimal manner, governmental agencies and business executives especially from developing, or less developed countries, which have also committed to implementing the UN's 17 SDGs and will gradually start to produce (more) solar PV electricity, and need to be aware, in a timely manner, of how should they manage, sustainably, the end-of-life phase for Photovoltaics systems, etc.

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Glossary And Abbreviations

B2B	Business To Business
B2C	Business To Consumer
BoS	Balance of System
CdTe	Cadmium Telluride
CIGS	Copper Indium Gallium Selenide
c-Si	Crystalline Silicon
EBITDA	Earnings Before Interest, Taxes, Depreciation, and Amortization
EU	European Union
IEA PVPS	International Energy Agency: the Photovoltaic Power System Programme
IoT	Internet of Things
IRENA	International Renewable Energy Agency
Kg	Kilogram
KPI	Key Performance Indicator
LCA	Life Cycle Analysis, or Life Cycle Assessment
LCOE	Levelized Cost of Electricity
MW, GW, kW	MegaWatt, GigaWatt, KiloWatt
PAYG	Pay As You Go
PAYP	Pay As You Put
RnD	Research and Development
Stiftung EAR	Germany's Stiftung Elektro-Altgeräte Register
WEEE	Waste Electrical and Electronic Equipment
Wp	Watt Peak

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Appendix 1 Fifty Largest Bavaria/Germany Solar Power Plants

Table 19 Fifty Largest Bavaria PV Power Plants Commissioned 2000-2010 (adapted solar-prinz.de)

Nr.	Name	Nearest Municipality	Capacity (MWp)	Number Modules	Ops.Start	Federal State	Entrepreneur	PV Module Manufacturer
1	Solarpark Straßkirchen	Regensburg	54	225.000	2009	Bayern	Q-Cells / MEMC	Q-Cells
8	Solarpark Mengkofen	Regensburg	21,78	98.978	2009	Bayern	SolarWorld AG	SolarWorld
10	Solarpark Helmeringen I+II	Lauingen/Donau	19,44	270.000	2009	Bayern	Gehrlicher Solar AG, SWM	First Solar
12	Solarpark Thüngen	Main-Spessart	18	85.000	2010	Bayern		Conergy
13	Solarpark Moos	Würzburg	15,8	160.000	2010	Bayern	Phoenix Solar AG	
14	Solarpark Allmannshofen I+II	Allmannshofen	15	200.000	2009	Bayern	Juwi Solar GmbH	First Solar
17	Solarpark Gut Erlasee	Arnstein	12	17.570	2006	Bayern	SOLON AG	Solarstrom AG
18	Solarpark Laudenbach	Würzburg	11,15	48.912	2010	Bayern	Solarhybrid AG	Renersola
20	Solarpark Pocking I	Passau	10	57.912	2006	Bayern	Shell Solar GmbH	Shell Solar
27	Solarpark Gottmansdorf	Heilsbronn	8,21		2009	Bayern	Beck Energy GmbH	First Solar
32	Solarpark Nordendorf	Augsburg	7,4	35.000	2009	Bayern	Sinosol AG	
34	Solarpark Großhaslach	Ansbach	6,95		2009	Bayern		First Solar
35	Solarpark Münchberg	Oberfranken	6,84	29.760	2010	Bayern	Wirsol Solar AG	Yingli
36	Solarpark Ernsthof Ost (Teil vom Tauberlandpark)	Wertheim	6,8	31.280	2010	Bayern	relatio SP	
39	Solarpark Thiersheim/Neuenreuth	Thiersheim	6,35		2009	Bayern	Beck Energy GmbH	
41	Solarpark Repperndorf	Steinhügel, Neuburg	6,29		2009	Bayern		First Solar
42	Solarpark Mühlhausen bei Neumarkt, (Bestandteil des Bavaria Solarparks)	Mühlhausen	6,27	36.000	2004	Bayern	PowerLight Corporation, Scatec Solar	Sharp
43	Solarpark Schwarzhof	Maxhütte-Haidhof	6,19	28.000	2010	Bayern	Krinner GmbH	
44	Solarpark Schwarzach am Main	Schwarzach am Main	6,11		2009	Bayern	Beck Energy GmbH	First Solar
45	Solarpark Haag	Gutenstetten	6	80.000	2009	Bayern	Gehrlicher Solar AG	First Solar
47	Solarpark Oettingen	Donau-Ries	6		2010	Bayern		
49	Solarpark Windach/Moorenweis	Fürstenfeldbruck	5,94	33.932	2007	Bayern		Ecostream/Solarfun
52	Solarpark Igling-Buchloe	Ost-Allgäu	5,79	78.210	2008	Bayern	EPURON GmbH	First Solar
53	Solarpark Biederbach	Wolframs-Eschenbach	5,7	32.992	2009	Bayern	SolarWorld AG	SolarWorld
54	Solarpark Köching II	Aldersbach, Niederbayern	5,67	32.400	2009	Bayern	Solea AG	Solea
57	Solarpark Oberottmarshausen	Bobingen	5,57	76.800	2007	Bayern	Juwi Solar GmbH	First Solar
58	Solarpark Pfeffenhausen/Egglhausen I+II	Pfeffenhausen	5,56	38.000	2008	Bayern	Scatec Solar	
59	Solarpark Püssensheim	Prosselsheim	5,53		2010	Bayern		
62	Solarpark Miegersbach	Dachau	5,27	32.028	2005	Bayern	Phoenix Solar AG	Phoenix/Photowatt International
63	Solarpark Ergoldsbach	Landshut	5,17		2010	Bayern	GEOSOL	
64	Solarpark Krumbach I+II	Krumbach	5,16		2009	Bayern	Scatec Solar	
65	Solarpark Kleinaitingen I, Allgäu	Kleinaitingen	5,08	68.500	2007	Bayern	Juwi Solar GmbH	First Solar
68	Solarpark Thierhaupten	Augsburg	5	28.500	2007	Bayern		Canadian Solar
69	Solarpark Baar	Augsburg	4,8	66.240	2007	Bayern	SunTechnics (jetzt Conergy)	First Solar
70	Solarpark Vestenbergsgreuth	Vestenbergsgreuth	4,8		2010	Bayern	SolarWorld AG	SolarWorld
71	Solarpark Malching	Fürstenfeldbruck	4,73		2009	Bayern	Phoenix Solar AG	
72	Solarpark Holzgünz	Mindelheim, Unterallgäu	4,68	62.800	2010	Bayern	Juwi Solar GmbH	First Solar
73	Dachanlage Dehner Gartencenter	Rain	4,64	66.000	2009	Bayern	Walter konzept	First Solar
74	Dachanlage Immler (50 Dächer)	Durach	4,56	45.219	2008	Bayern		First Solar, Baoding Yingli Solar
75	Solarpark Greding/Grafenberg I+II	Greding	4,55		2009	Bayern	gp Solar	First Solar
77	Solarpark Thalern/Gerolsbach	Pfaffenhofen an der Ilm	4,5		2010	Bayern		
78	Solarpark Müncherlbach	Heilsbronn	4,5		2009	Bayern	Beck Energy GmbH	First Solar
80	Solarpark Höttingen	Weißenburg	4,42	57.000	2009	Bayern	Beck Energy GmbH	First Solar
81	Solarpark Vilgertshofen-Pflugdorf	Landsberg a. Lech	4,36	59.940	2008	Bayern	Draka Services	First Solar
82	Solarpark Hurlach	Landsberg a. Lech	4,3	25.820	2007	Bayern	SolarWorld AG	SolarWorld, Canadian Solar
83	Solarpark Horgach/Auerbach	Augsburg	4,3		2010	Bayern		
85	Solarpark Froschham	Augsburg	4,17	57.510	2008	Bayern		First Solar
86	Solarpark Miesberg	Pfaffenhofen an der Ilm	4,1	55.050	2009	Bayern		

Appendix 2 Sample Report Of Freight Environmental Impacts

Calculated based on EcoTransIT World, http://www.ecotransit.org/calculation.en.html for 10 ton truck on Diesel

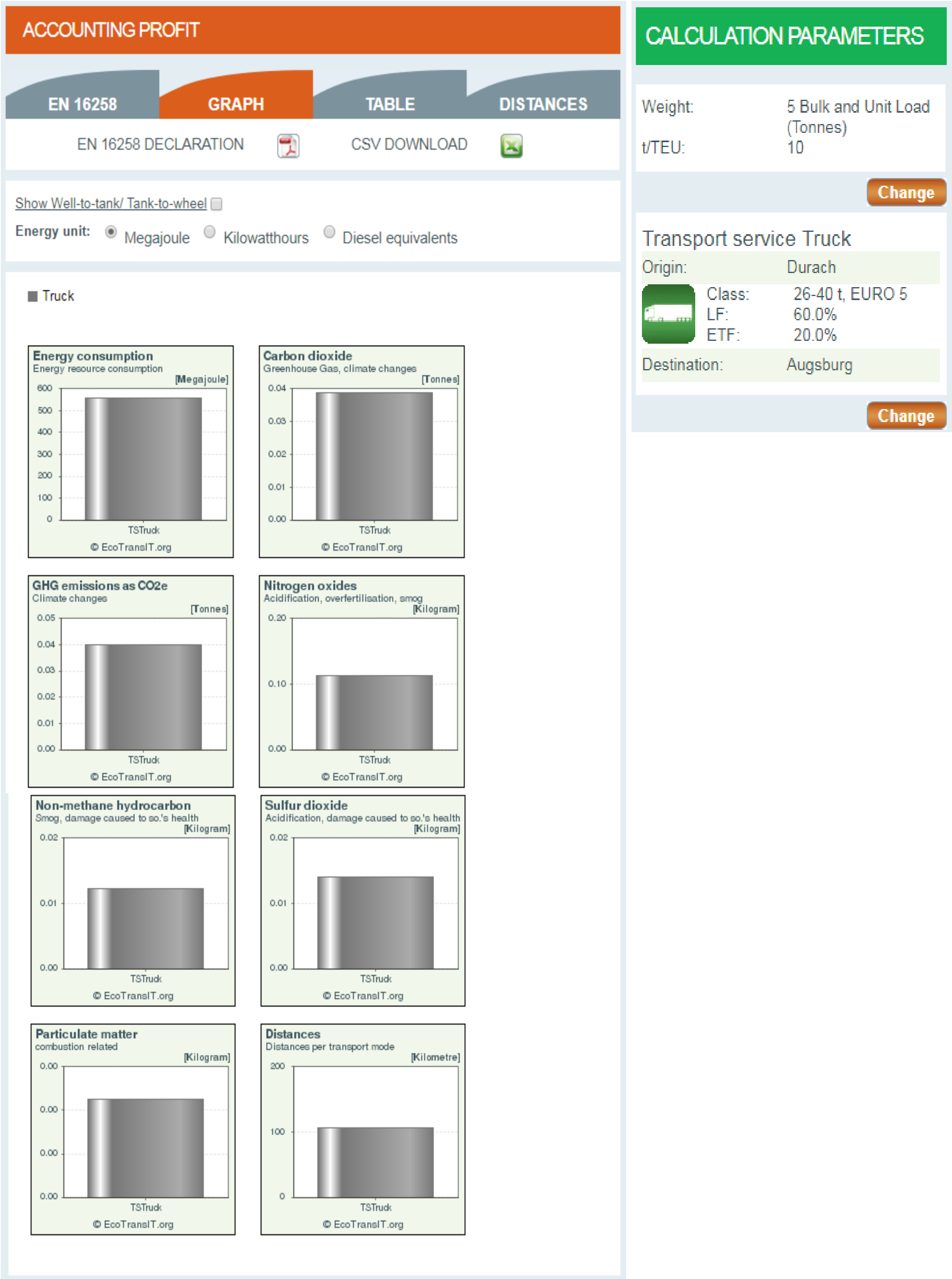


Figure 33 Sample Report Of Freight Transport Environmental Impacts

-(based on EcoTransIT World 2017)

Appendix 3 PV Waste Transport And Emissions Costs Model

Table 20 PV Waste Transport Costs And GHG Emissions Calculation Model

MODEL PARAMETER	VALUE	MEASUREMENT UNIT	INFORMATION SOURCE
PV Panels - Freight Transport - Logistics Costs			
PV Panels Weight for Transport (Truck Payload)	**1.000,00**	**[Ton]**	
Medium Size Heavy Duty Vehicle (10 Ton GVW)	**5,00**	**[Ton] Max. Payload Capacity**	*Assumed ideal Max.Payload Capacity
Travel Distance	**100,00**	**[KM]**	
Fuel Price (Diesel)	1,15	[EUR/Liter]	www.mylpg.eu/stations/germany/prices
Vehicle Fuel Efficiency	34,00	[Liter/100 KM]	www.transportenvironment.org
	0,34	[Liter/ KM]	
# Trips at Max. Payload Capacity	200,00	[Trips]	
Total Distance Travelled	**20.000,00**	**[KM]**	
Total Fuel Used for Total Distance Travelled	6.800,00	[Liter]	
Total Fuel Cost	7.813,20	[EUR]	
Truck Driver Salary (1.957 - 2.527 € pro Monat)	15,00	[EUR/Hour]	www.gehalt.de/einkommen/
Average Driving Speed	60,00	[KM/Hour]	
Total Driving Hours	333,33	[Hour]	
Total Driver Salary for Given Travel Distace	5.000,00	[EUR]	
Overhead Logistics Costs - Service Fee	1,50		*Assumed from Choi and Fthenakis (2010)
Total Logistics Costs	7.500,00	[EUR]	
TOTAL Transport Costs	**15.313,20**	**[EUR]**	
Specific Transport Cost	**0,1531**	**[EUR/Ton/KM]**	
PV Panels - Freight Transport - Emissions Budget			
GreenHouse Gas Emissions as CO_2 equivalent			
Carbon Dioxide WTT (Well-To-Tank)	1,8868	[Ton]	www.ecotransit.org
Carbon Dioxide TTW (Tank-To-Wheel)	5,6604	[Ton]	www.ecotransit.org
Carbon Dioxide WTW (Well-To-Wheel)	7,5472	[Ton]	WTW = WTT + TTW
Nitrogen Oxides (NOx)			
NOx WTT (Well-To-Tank)	1,8868	[KG]	www.ecotransit.org
NOx TTW (Tank-To-Wheel)	16,9811	[KG]	www.ecotransit.org
NOx WTW (Well-To-Wheel)	18,8679	[KG]	WTW = WTT + TTW
Sulphur Dioxide (SO_2)			
SO_2 WTT (Well-To-Tank)	1,8491	[KG]	www.ecotransit.org
SO_2 TTW (Tank-To-Wheel)	0,0377	[KG]	www.ecotransit.org
SO_2 WTW (Well-To-Wheel)	1,8868	[KG]	WTW = WTT + TTW
Particulate Matter (PM)			
PM WTT (Well-To-Tank)	0,1887	[KG]	www.ecotransit.org
PM TTW (Tank-To-Wheel)	0,3774	[KG]	www.ecotransit.org
PM WTW (Well-To-Wheel)	0,5660	[KG]	WTW = WTT + TTW
Carbon Tax	20,00	[EUR / Ton CO_{2e}]	* If a 20 EUR tax per Ton of CO2 is introduced
TOTAL Costs For Transport Related Carbon Emissions	**150,94**	**[EUR]**	
Specific Transport Related Carbon Emissions Costs	**0,0015**	**[EUR/Ton/KM]**	

Appendix 4 LP Model – PV Panel Waste Allocated to Recycling Centers

Table 21 LP Model: Minimization Of Bavaria RCi Logistics Costs, Base Scenario (2024)

DISTANCE MATRIX [KM]	RC_1	RC_2	RC_4	RC_5	RC_6	RC_7	CC_j CAPACITY [TON/YEAR] ↓ / RC_i Annual → Efficiency [%]	RC_1 [TON/YEAR] 90,00%	RC_2 [TON/YEAR] 98,00%	RC_4 [TON/YEAR] 88,00%	RC_5 [TON/YEAR] 88,00%	RC_6 [TON/YEAR] 88,00%	RC_7 [TON/YEAR] 98,00%
CC_1	227	308	160	211	105	307	743	0	0	0	0	743	0
CC_2	36	223	105	118	132	188	1.966	0	0	1.871	95	0	0
CC_3	124	170	208	64	151	86	911	0	0	0	0	0	911
CC_4	262	91	293	125	224	27	1.573	0	0	0	0	0	1.573
CC_5	0	281	80	149	148	245	3.364	1.824	0	1.540	0	0	0
CC_6	16	269	91	163	169	259	730	0	0	730	0	0	0
CC_7	52	273	30	164	121	272	691	0	0	691	0	0	0
CC_8	64	204	133	98	150	164	786	0	0	0	786	0	0
CC_9	107	373	132	276	249	272	598	0	0	598	0	0	0
CC_{10}	56	297	33	188	145	291	1.398	0	0	1.398	0	0	0
CC_{11}	118	166	114	57	71	165	596	0	0	0	596	0	0
CC_{12}	189	98	210	52	151	73	786	0	0	0	0	0	786
CC_{13}	154	131	190	27	132	102	1.666	0	0	0	1.666	0	0
CC_{14}	20	272	85	166	172	262	666	0	0	666	0	0	0
CC_{15}	48	318	138	200	206	217	676	676	0	0	0	0	0
CC_{16}	42	332	63	223	179	285	1.135	0	0	1.135	0	0	0
CC_{17}	123	263	73	166	66	262	678	0	0	0	0	678	0
CC_{18}	63	278	132	181	165	177	2.548	0	0	0	0	0	2.548
CC_{19}	283	123	315	147	246	41	2.359	0	0	0	0	0	2.359
CC_{20}	167	211	144	113	26	210	811	0	0	0	0	811	0
CC_{21}	66	360	91	212	208	263	613	0	0	613	0	0	0
CC_{22}	131	161	127	55	74	161	822	0	0	0	822	0	0
CC_{23}	230	75	232	96	163	161	896	0	896	0	0	0	0
CC_{24}	78	372	104	225	220	293	759	0	0	759	0	0	0
CC_{25}	246	329	196	231	125	328	1.311	0	0	0	0	1.311	0

	Total	RC_1	RC_2	RC_4	RC_5	RC_6	RC_7
RC_i ALLOCATED PV Waste [TON / YEAR]	29.080	2.500	896	10.000	3.965	3.542	8.176
RC_i Usage of FULL CAPACITY [%]	68,42%	100,00%	8,96%	100,00%	79,30%	70,85%	81,76%
RC_i FULL CAPACITY [TON / YEAR]	42.500	2.500	10.000	10.000	5.000	5.000	10.000
TRANSPORT COSTS CC => RC [EUR / YEAR]	327.667	4.969	10.293	121.654	32.525	47.100	111.125
TRANSPORT COSTS RC => LF [EUR / YEAR]	9.693	957	69	4.593	1.821	1.627	626
Total TRANSPORT COSTS RC [EUR / YEAR]	337.359	5.926	10.361	126.247	34.347	48.727	111.751
Landfill COSTS RC [EUR / YEAR]	278.557	27.500	1.972	132.000	52.340	46.758	17.988
Total RC Logistics COSTS [EUR / YEAR]	953.276	39.353	22.695	384.495	121.033	144.212	241.489
Carbon Emissions CC => RC [Ton Carbon / YEAR]	160,52	2,43	5,04	59,60	15,93	23,07	54,44
Carbon Emissions COSTS RC => LF [Ton Carbon / YEAR]	4,75	0,47	0,03	2,25	0,89	0,80	0,31
Total RC Transport Carbon Emissions [Ton Carbon / YEAR]	165,26	2,90	5,08	61,85	16,83	23,87	54,74

Appendix 5 Distance Matrix Between Selected CCj and RCi In Bavaria

Table 22 Bavaria - Distance Matrix Between Selected CC_j and RC_i (based on Google Maps 2017)

DISTANCE MATRIX [KM]		RC_1	RC_2	RC_3	RC_4	RC_5	RC_6	RC_7
		Augsburg	Coburg	Ingolstadt	München	Nürnberg	Regensburg	Würzburg
CC_1	Aldersbach, Niederbayern	227	308	197	160	211	105	307
CC_2	Allmannshofen	36	223	60	105	118	132	188
CC_3	Ansbach	124	170	134	208	64	151	86
CC_4	Arnstein	262	91	218	293	125	224	27
CC_5	Augsburg	0	281	84	80	149	148	245
CC_6	Bobingen	16	269	105	91	163	169	259
CC_7	Dachau	52	273	76	30	164	121	272
CC_8	Donau-Ries	64	204	66	133	98	150	164
CC_9	Durach	107	373	204	132	276	249	272
CC_{10}	Fürstenfeldbruck	56	297	99	33	188	145	291
CC_{11}	Greding	118	166	39	114	57	71	165
CC_{12}	Gutenstetten	189	98	135	210	52	151	73
CC_{13}	Heilsbronn	154	131	116	190	27	132	102
CC_{14}	Kleinaitingen	20	272	108	85	166	172	262
CC_{15}	Krumbach	48	318	142	138	200	206	217
CC_{16}	Landsberg a. Lech	42	332	134	63	223	179	285
CC_{17}	Landshut	123	263	76	73	166	66	262
CC_{18}	Lauingen/Donau	63	278	88	132	181	165	177
CC_{19}	Main-Spessart	283	123	240	315	147	246	41
CC_{20}	Maxhütte-Haidhof	167	211	118	144	113	26	210
CC_{21}	Mindelheim, Unterallgäu	66	360	163	91	212	208	263
CC_{22}	Mühlhausen	131	161	52	127	55	74	161
CC_{23}	Oberfranken	230	75	158	232	96	163	161
CC_{24}	Ost-Allgäu	78	372	175	104	225	220	293
CC_{25}	Passau	246	329	195	196	231	125	328
CC_{26}	Pfaffenhofen an der Ilm	64	238	41	54	129	86	237
CC_{27}	Pfeffenhausen	121	253	57	98	160	56	252
CC_{28}	Prosselsheim	253	93	198	273	141	204	17
CC_{29}	Rain	52	222	46	120	116	123	187
CC_{30}	Regensburg	147	210	98	124	113	0	209
CC_{31}	Schwarzach am Main	246	96	184	259	91	190	26
CC_{32}	Steinhügel, Neuburg	247	329	196	197	232	126	329
CC_{33}	Thiersheim	279	132	230	256	174	139	192
CC_{34}	Vestenbergsgreuth	227	99	148	223	55	154	62
CC_{35}	Weißenburg	87	166	54	136	61	147	157
CC_{36}	Wertheim	286	152	242	316	149	248	43
CC_{37}	Wolframs-Eschenbach	118	162	125	200	56	142	101
CC_{38}	Würzburg	245	110	202	277	109	208	0

Appendix 6 Assumptions Used For The Linear Optimization Model

Table 23 Assumptions Used For The Linear Optimization Model

	Assumption			Source
[1]	PV Panel Weight-to-Power Ratio, approximated for year 2000	120	[Ton PV Panel/MWe]	Based on Ref. [10], "End-of-Life Management: Solar Photovoltaic Panels"
[2]	PV Panel Waste Transport Cost	0,1531	[EUR/Ton/KM]	As calculated in **Appendix 3** for the LP Model, Base Scenario
[3]	For PV Waste transport: Medium Size **Truck** (Heavy Goods Vehicle) with an average Gross Vehicle Weight of 10 Ton and a maximum (optimal) **payload of 5 Ton**			Author proposal, based on PV Waste amounts available for Base Scenario, and expected limited storage capacities at Collection Centers
[4]	Truck (Diesel) Fuel Economy	34	[Liter/KM]	Based on Ref. [5]: Transport and Environment, 2015 - "Lorry CO2 – why Europe needs standards"
[5]	Average distance between RC_i and the closest Landfill site	25	[KM]	This assumption would likely be subjected to high variation, based on the chosen location for every RC_i, in real life scenarios
[6]	Landfill Gate Fee plus Landfill Tax	110	[EUR/Ton]	Based on current WRAP (http://www.wrap.org.uk/) and CEWEP (Confederation of European Waste-To-Energy Plants, http://www.cewep.eu/information/data/landfill/index.html), Ref. [8] and [9]
[7]	Specific Cost due to Transport related Carbon Emissions	0,0015	[EUR/Ton/KM]	As calculated in **Appendix 3** for the LP Model, Base Scenario, for an assumed Carbon Tax of 20 EUR/Ton

Appendix 7 Impact Of Recycling Center Capacity Design On Logistics Costs

Table 24 Impact Of Recycling Center Capacity Design On Total Logistics Costs

Scenario 3.1 - RC_2 Designed With 10.000 Ton/Year Capacity

DISTANCE MATRIX [KM]	RC_2 Coburg [KM]	RC_3 Ingolstadt [KM]	CCj CAPACITY [TON/2024]	RC2 [TON/2024]	RC3 [TON/2024]	CCj CAPACITY [TON/2025]	RC2 [TON/2025]	RC3 [TON/2025]	CCj CAPACITY [TON/2026]	RC2 [TON/2026]	RC3 [TON/2026]	CCj CAPACITY [TON/2027]	RC2 [TON/2027]	RC3 [TON/2027]	CCj CAPACITY [TON/2028]	RC2 [TON/2028]	RC3 [TON/2028]
CC_4	91	218	1573	1.573	0	1.725	1.725	0	1.693	1.693	0	2.732	2.732	0	2.782	2.782	0
CC_{11}	166	39	1560	0	1.560	1.710	0	1.710	1.679	0	1.679	1.509	0	1.509	1.537	0	1.537
CC_{12}	98	135	2380	2.380	0	2.609	2.609	0	2.561	2.561	0	2.593	0	2.593	2.640	0	2.640
CC_{22}	161	52	2100	0	2.100	2.302	0	2.302	2.260	0	2.260	2.166	0	2.166	2.206	0	2.206
CC_{23}	75	158	1940	1.940	0	2.127	2.127	0	2.088	2.088	0	2.189	0	2.189	2.229	0	2.229
CC_{26}	238	41	2250	0	2.250	2.467	0	2.467	2.421	0	2.421	1.428	0	1.428	1.454	0	1.454
CC_{28}	93	198	1500	1.500	0	1.645	1.645	0	1.614	1.614	0	3.008	3.008	0	3.062	3.062	0
CC_{29}	222	46	1960	0	1.960	2.149	0	2.149	2.109	0	2.109	1.668	0	1.668	1.698	0	1.698
CC_{31}	96	184	900	900	0	987	987	0	969	969	0	6.700	4.260	2.440	6.822	4.156	2.666
CC_{35}	166	54	6000	0	6.000	6.579	0	6.579	6.457	0	6.457	758	0	758	771	0	771
FIVE YEARS TOTAL			Total Sent RC_i [Ton/Year]	8.293	13.870	Total Sent RC_i [Ton/Year]	9.093	15.207	Total Sent RC_i [Ton/Year]	8.924	14.926	Total Sent RC_i [Ton/Year]	10.000	14.750	Total Sent RC_i [Ton/Year]	10.000	15.200
3.611.913	[EUR]		Total Transport Costs [EUR/Year]	568.669		Total Transport Costs [EUR/Year]	623.501		Total Transport Costs [EUR/Year]	611.955		Total Transport Costs [EUR/Year]	893.311		Total Transport Costs [EUR/Year]	914.477	
9.438.200	[Ton*KM]		Total [Ton X KM]	1.424.233		Total [Ton X KM]	1.561.560		Total [Ton X KM]	1.532.643		Total [Ton X KM]	2.429.793		Total [Ton X KM]	2.489.971	

Scenario 3.1 - RC_2 Designed With 20.000 Ton/Year Capacity

DISTANCE MATRIX [KM]	RC_2 Coburg [KM]	RC_3 Ingolstadt [KM]	CCj CAPACITY [TON/2024]	RC2 [TON/2024]	RC3 [TON/2024]	CCj CAPACITY [TON/2025]	RC2 [TON/2025]	RC3 [TON/2025]	CCj CAPACITY [TON/2026]	RC2 [TON/2026]	RC3 [TON/2026]	CCj CAPACITY [TON/2027]	RC2 [TON/2027]	RC3 [TON/2027]	CCj CAPACITY [TON/2028]	RC2 [TON/2028]	RC3 [TON/2028]
CC_4	91	218	1573	1.573	0	1.725	1.725	0	1.693	1.693	0	2.732	2.732	0	2.782	2.782	0
CC_{11}	166	39	1560	0	1.560	1.710	0	1.710	1.679	0	1.679	1.509	0	1.509	1.537	0	1.537
CC_{12}	98	135	2380	2.380	0	2.609	2.609	0	2.561	2.561	0	2.593	2.593	0	2.640	2.640	0
CC_{22}	161	52	2100	0	2.100	2.302	0	2.302	2.260	0	2.260	2.166	0	2.166	2.206	0	2.206
CC_{23}	75	158	1940	1.940	0	2.127	2.127	0	2.088	2.088	0	2.189	2.189	0	2.229	2.229	0
CC_{26}	238	41	2250	0	2.250	2.467	0	2.467	2.421	0	2.421	1.428	0	1.428	1.454	0	1.454
CC_{28}	93	198	1500	1.500	0	1.645	1.645	0	1.614	1.614	0	3.008	3.008	0	3.062	3.062	0
CC_{29}	222	46	1960	0	1.960	2.149	0	2.149	2.109	0	2.109	1.668	0	1.668	1.698	0	1.698
CC_{31}	96	184	900	900	0	987	987	0	969	969	0	6.700	6.700	0	6.822	6.822	0
CC_{35}	166	54	6000	0	6.000	6.579	0	6.579	6.457	0	6.457	758	0	758	771	0	771
FIVE YEARS TOTAL			Total Sent RC_i [Ton/Year]	8.293	13.870	Total Sent RC_i [Ton/Year]	9.093	15.207	Total Sent RC_i [Ton/Year]	8.924	14.926	Total Sent RC_i [Ton/Year]	17.221	7.529	Total Sent RC_i [Ton/Year]	17.535	7.665
3.301.252	[EUR]		Total Transport Costs [EUR/Year]	568.669		Total Transport Costs [EUR/Year]	623.501		Total Transport Costs [EUR/Year]	611.955		Total Transport Costs [EUR/Year]	741.820		Total Transport Costs [EUR/Year]	755.307	
8.428.601	[Ton*KM]		Total [Ton X KM]	1.424.233		Total [Ton X KM]	1.561.560		Total [Ton X KM]	1.532.643		Total [Ton X KM]	1.937.469		Total [Ton X KM]	1.972.696	

Appendix 8 Proposed PV Panel Collection And Recycling Centers - Bavaria

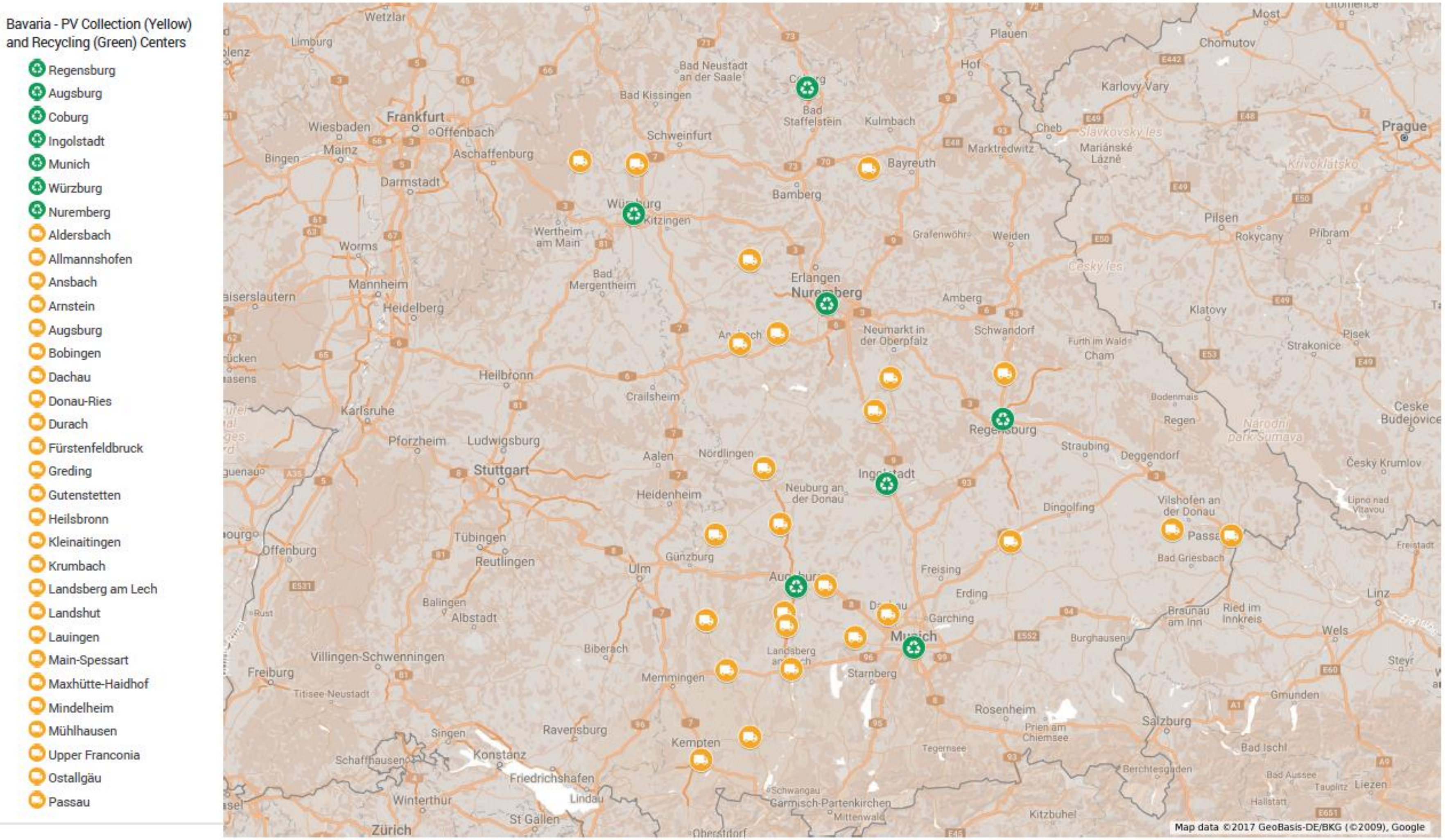
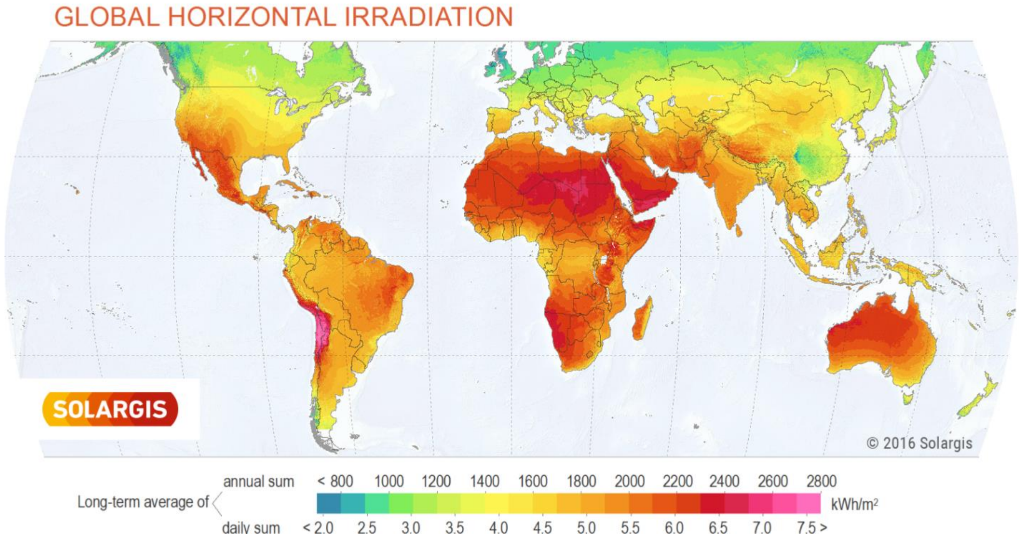


Figure 34 Bavaria PV Collection And Recycling Centers - Proposed Locations (based on Google Maps)

Appendix 9 World – Global Horizontal Irradiation, Direct Normal Irradiation



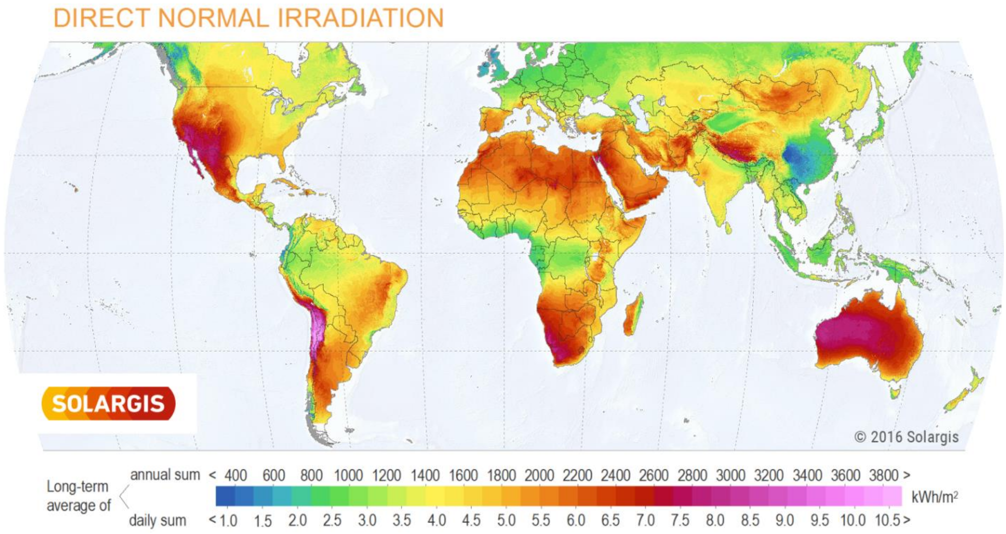


Figure 35 World Solar Global Horizontal Irradiation and Direct Normal Irradiation (from SolarGis.com)