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Estimation of Quantities of Waste Materials for Photovoltaic Installations in Crete Island

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***Abstract*—This paper aims to estimate the amount of waste materials for photovoltaic (PV) installations in Crete Island. Crete is the largest Greek island and constitutes the largest autonomous power system in Greece. The analysis includes the impact of the basic components of a PV system: PV panels, PV mounting system, cables, and inverters. The results show that significant amounts of waste materials will be produced in the period 2030-2038. Moreover, this study generalizes the results for the entire Greek territory.**

***Keywords*—crystalline silicon photovoltaics, recycling, waste electrical and electronic equipment (WEEE), Crete**

I. Introduction

Product life cycle management and sustainable development have become leading ideas around manufacturing in the 21st century. Concerning products of electrical and electronic equipment (EEE), new approaches examining their whole environmental influence through their whole life cycle have been developed during the last years. However, being proactive and innovative with respect to sustainable development is often regarded successful rather in the long term than in the short term. In particular, design, manufacturing and end-of-life (EOL) treatment strategies considering the ecological, economical and social challenges with special reference to disassembly and recycling, are currently addressed by various researchers [1]-[2]. It is during the design and manufacturing stages that considerably determine how wealth is created and what the relation is between useful functionality and exploited resources.

The last years we are facing an increased interest in new photovoltaic (PV) installations which are heavily subsidized [3]. As a result, a large number of utility and small size installations are under development, not only in Greece but in Europe and worldwide. This leads to an ever-increasing demand for a sustainable method of disposal of PV modules when reaching EOL [4]-[5], but also for those modules that are damaged or substituted for any reason.

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This paper aims to estimate the amount of waste materials for PV installations. Calculations are implemented initially for Crete Island, and afterwards they are generalized for the entire Greek territory. The paper is organized as follows. Section II present an overview of PV systems and PV recycling methods. Section III describes the power system of Crete Island. Section IV includes the considerations and data needed for the analysis. Section V presents and analyzes the results, whereas Section VI concludes the paper.

II. PV Systems and Recycling Methods

PVs convert sunlight into DC electricity. However, most PV installations either serve a nearby AC demand or sell electricity to AC grid. In these cases, the addition of inverters (which convert DC to AC) in the PV system is also needed. There are currently three generations of technology for PV panels:

- *Crystalline silicon (c-Si) PVs*: They can be monocrystalline silicon (mono-Si) or polycrystalline silicon (poly-Si) solar cells. C-Si PV modules are used in almost all PV installations in Greece.
- *Thin film PVs*: They include one or more thin layers of PV material on a surface. Their basic types are amorphous silicon (a-Si) PVs, cadmium telluride – (CdTe) PVs, and copper indium (gallium) selenide (CIS or CIGS).
- *Technologies under development*: They include organic PVs, multi-junction cells, etc. These technologies aim at higher efficiencies and/or lower costs.

Lifetime of dominant PV technologies today is around 25-30 years. The main components of a c-Si PV module (i.e., the most dominant technology in Greece) include [6]:

- Composed glass to protect the cells from damage
- Laminating mostly consists of ethylene vinyl acetate (EVA). The solar cells are embedded in the two layers of laminating
- Mono-Si or poly-Si solar cells which are connected with copper ribbons
- Weatherproof plastic backing made from Polyvinyl fluoride (PVF) and Polyethylene (PET)
- Junction box for connecting the PV modules to each other

TABLE I. LIST OF KNOWN PV RECYCLING ACTIVITIES (MAINLY LABORATORY)

Operator	Procedure	Size/Stage of Development	PV Technology
Isofoton	Cell recycling, Swelling, Shredding, Repairable module	Laboratory	Crystalline
Photovoltech	Repairable module	Laboratory	Crystalline
AIST, Sharp, Asahi	Wafer recycling with mineral acids, Solvent swelling (Cellsepa-Process), Repairable module	Laboratory	Crystalline
BP Solar, Soltech, Seghers	Wafer recycling with mineral acids, Wafer recycling in fluidized bed	Laboratory/ Technical College	Crystalline
Pilkington Solar International	Thermal separation	Laboratory/ Technical College	Crystalline
Siemens Solar, Shell Solar, Showa Shell	Ferrosilicon production, High pressure water jet	Laboratory	Crystalline, thin film
Other	Module shredder, Mechanical separation, Acid treatment, Smelter, MWI, Concrete aggregates, Road construction	Laboratory	Crystalline, thin film
Disposer	Removal of frames and cable, Disposal, Incineration	Production	All

Currently there are two tested treatment and recycling methods specific for PV panels: one for the c-Si PV panels (by Deutsche Solar), and one for CdTe PV panels (by First Solar). Both processes are not economically viable as stand alone as the generated waste is not yet adequate. Deutsche Solar PV panel treatment process was introduced in 2003, and it has been demonstrated for a variety of types and sizes of c-Si PV panels [7]. First solar CdTe PV panel treatment process was introduced in 2003 and constitutes a more integrated solution. Recycling takes place at each of First Solar's manufacturing locations, contact information is provided on each panel, collection and recycling are free for customers, and the whole program is prefunded (at the time of sale of each panel). While it is mainly suitable for CdTe panels, it has been also tested for CIS and CIGS technology. Apart from these two methodologies, many more recycling techniques and activities (mainly laboratory) are in progress, which are listed in Table I [8]-[9].

The PV industry in Europe has started building an infrastructure for recycling [10] and this served them well in complying with the Waste Electrical and Electronic Equipment (WEEE) Directive. Originally launched in 2003, the WEEE Directive regulates the treatment of electrical and electronic waste at the end of their life cycle. The directive has been recasted twice in 2008 and 2012, resulting into an enlarged scope to include many new additional products. Photovoltaic (PV) panels were introduced in the latest revision of 2012 (Directive 2012/19/EU [11]). Under this Directive, producers of PV panels have become responsible for the disposal and recycling of the modules they sell in one or more European Union Member States.

III. Description of Cretan Power System

Crete is the largest Greek island with approximately 8500km^2 and the fifth in Mediterranean Sea with more than 600,000 inhabitants, tripling in summer period. It is divided into four regional units, which are from west to east: Chania, Rethymno, Heraklion, and Lasithi. Crete also consists the largest autonomous power system in Greece, (i.e., it has to serve its electricity consumption by itself).

In order to achieve this, a large number of conventional units (steam turbines, diesel generators, gas turbines, and one combined cycle unit) have been installed in three power plants with total capacity of 813MW. Moreover, significant wind potential (especially in the eastern part) and solar potential (one of the highest in Europe) can be found in the island, which make Crete ideal for the installation of wind and solar technologies. As a result, already 20 wind farms have been installed with rated power of 183MW, whereas more than 2800 small PV systems have been installed, reaching a total of 95MW. Moreover, large solar thermal plants of around 40MW are expected to be installed on the east side of the island by 2016.

Renewable penetration is significant in Crete Island. In year 2012, wind and solar penetration was 20.5%. The share for wind turbines was 15.8% and for PVs was 4.7%. It is worth mentioning that there are interconnection plans between the Cretan power system and the main Greek power system, as well as an interconnection plan – the Euro-Asia Interconnector – linking Crete, Cyprus and Israel. Should these plans implemented, the renewable energy penetration in the island is expected to increase significantly (already there are 1000MW of authorized wind parks) and may make Crete an exporter of renewable produced electricity. However, these actions are not planned to be implemented before 2020. Until then, the amount of new wind turbines and PV installations is planned to be very limited, due to operational constraints of the autonomous Cretan power system.

As a measure to establish a more environmental friendly energy system, Greek Government has import new laws in order to expand renewable generation capacity using guaranteed feed-in tariffs (FiTs). The amount of FiTs depends on the renewable technology, location, size, and year of installation. PV systems are divided into two main categories: PV parks (with upper limit of 80kW$_p$ for Crete, and sale contract of 20 years), and PV installations on roofs (with upper limit of 10kW$_p$, higher FiTs, and sale contract of 25 years). Until now, more than 1000 PV parks and 1800 PV on roof systems have been installed in Crete. The first PV parks started to produce electricity in the first years of the previous decade. However, until 2009 their number was very limited. PV on roofs started to be installed in 2011. Figs 1 and 2 show information about PV installations in Crete. Data for these figures are provided in [12].

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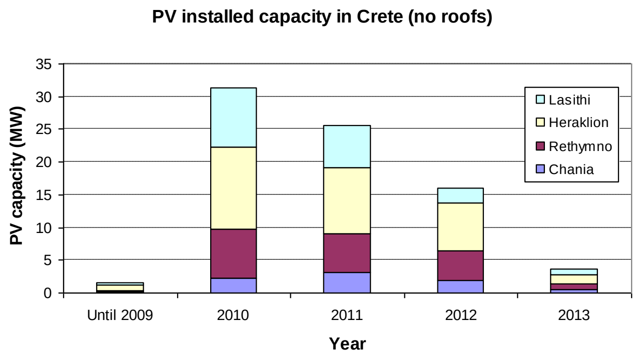

Figure 1. PV parks installed capacity in Crete.

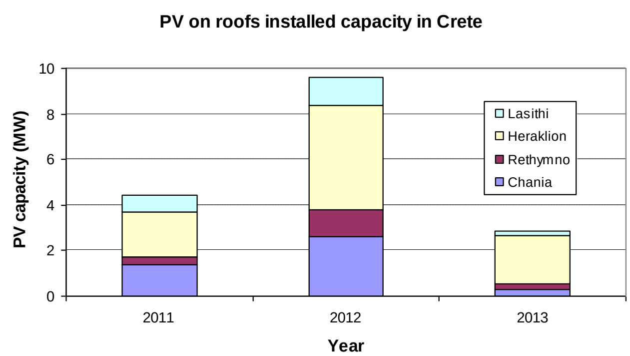

Figure 2. PV on roofs installed capacity in Crete.

IV. Case Study Considerations

In order to evaluate the amount of waste materials after EOL of PV modules, a typical c-Si panel of $215W_p$ rated power and 22kg weight has been considered for all PV installations. Table II presents the main components for this specific panel, as well as their weight ratio [8]. Apart from the components that are listed in Table II, a c-Si PV panel contains also very small quantities of Ag, Sn and Pb, which are not considered in this study.

TABLE II. COMPOSITION OF A TYPICAL C-SI PV PANEL (215 W_P)

PV Panel Component	Percentage	kg/kW_p
Glass	74.16%	77.3
Frame (Aluminum)	10.30%	10.7
EVA	6.55%	6.8
Solar cells	3.48%	3.3
Backing film (Tedlar)	3.60%	3.8
Adhesive, potting compound	1.16%	1.2
Copper (PV panel cables)	0.57%	0.59
Total weight (22kg / PV panel)		102.3

As it can be seen from Table II, the PV panel contains a small portion of copper, which corresponds to the cables that are connected to the junction box and used for connecting different panels electrically, as well as to the copper ribbons that connect the solar cells. However, additional cables are needed for connecting PV panels with the inverters. For this study, $6mm^2$ copper cables were considered, with copper compound of 57.6kg/km [13]. Their length depends on the size of PV installation. For installed capacities less than $10kW_p$ (PV on roofs and small PV parks), the total cable length is considered 50m. For a $80kW_p$ PV park, the total cable length is considered 500m. For PV parks of different capacities, total cable length is estimated by linear interpolation between these two values.

TABLE III. CONSIDERATIONS FOR PV MOUNTING SYSTEMS

PV Mounting System	Total weight (kg)	Aluminum (kg)	Steel (kg)	PV panels mounted	Share in Crete
Fixed (PV parks)	102.65	39.99	62.66	6	45.76%
Fixed with seasonal slope variation	105.00	22.40	82.60	4	3.23%
1-axis tracker	619.70	93.20	526.50	30	5.88%
2-axis tracker	15,690	5,232	10,458	108	27.41%
Fixed (PV on roofs)	109.60	109.60	0	5	17.72%

Regarding PV mounting systems, five different types have been considered: (a) fixed for PV parks, (b) fixed with seasonal slope variation, (c) 1-axis tracker, (d) 2-axis tracker, (e) fixed for PV on roofs. The first four types correspond to PV parks, whereas the last type corresponds to PV on roofs. Table III contains the considered information for the PV mounting systems, as well as their portion (per kW_p) in the PV installations of Crete. In all cases, the total weight does not include PV panels.

Lifetime of PV modules, mounting systems, cabling and inverters is considered 30 years [14]-[15]. This means that these parts are not needed to be replaced during PV sale contract time interval, which lasts 20-25 years. Moreover, the number of PV modules that are damaged or substituted for any reason is considered negligible. The amount of installed inverters is calculated via their capacity (which is considered equal to PV capacity), rather than their weight, because there are huge weight variations per installed inverter kW that depend on inverter size and technology.

V. Results and Discussion

A. *Crete Island*

Table IV presents the results for PV installations in Crete. Under present circumstances, significant amounts of waste are expected to be produced after year 2029. From the study of Table IV, it can be seen that at years 2034 and 2035 no wastes are produced, due to the fact that 2033 is the last year that sale contracts of PV parks exist, while 2036 is the first year that a PV on roof sale contract ends. The results show that significant amounts of valuable wastes are produced, mainly steel (from PV mounting systems), aluminum (mainly from PV mounting systems), glass and copper.

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The maximum amount of total PV panel waste is expected to take place in 2030 (3,213tn of PVs). Although this quantity is considered rather small compared to a typical PV recycling plant capacity (20,000tn/year [16]), the concept of a PV recycling plant installation within Crete has to be examined with care, since the transportation of PV wastes via ships to another loacation may result significant additional costs. In any case however, due to the rather short time interval of PV waste production (less than 10 years), it may be more effective to design this recycling plant with the option to recycle additional types of electrical and electronic equipment waste.

B. *Entire Greek Territory*

The above-mentioned procedure is generalized for the entire Greek territory (including Crete). The needed data for PV installations are provided in [12], whereas the case study considerations have been kept identical to those of Section IV. The entire Greek power system contains more than 14,000 PV parks and 41,000 PV on roof systems. The first PV parks started to produce electricity in the first years of the previous decade, but until 2008 their number was very limited. PV on roofs started to be installed in 2009 in small quantities (less than 100kW$_p$ in total), and from 2010 in significant quantities. At this time, PV installations are not expected to expand significantly in the following years. Figs 3 and 4 show information about PV installed capacity in the entire Greek territory.

The annual amount of waste is presented in Table V, and it covers the period 2028-2038. Similar to the Cretan case study, no wastes are expected to be produced in year 2034 and after year 2038. From the annual amount of PV panels, it can be concluded that several PV recycling plants have to be installed. As mentioned above, it may be more effective to design these plants with the option to recycle additional types of electrical and electronic equipment waste.

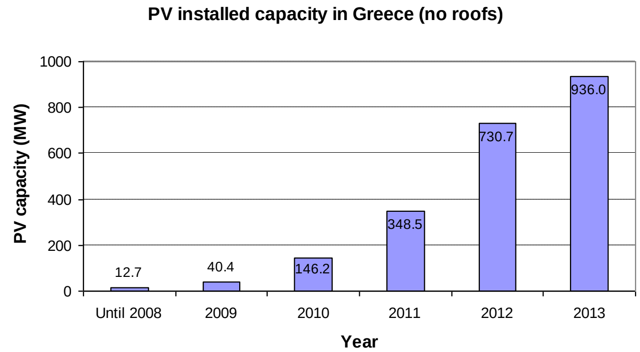

Figure 3. PV parks installed capacity in Greece.

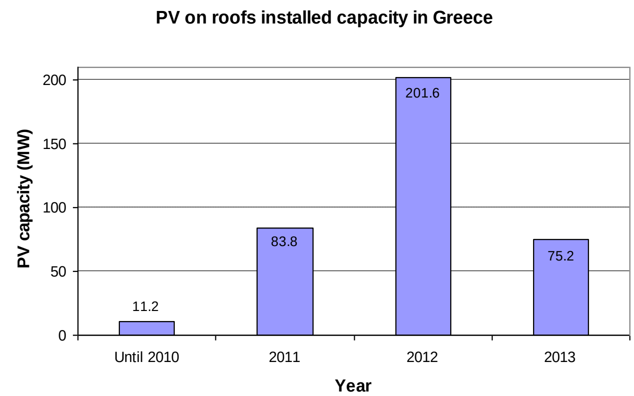

Figure 4. PV on roofs installed capacity in Greece.

TABLE IV. AMOUNT OF WASTE MATERIALS FOR PV INSTALLATIONS IN CRETE ISLAND

Year	PV weight (tn)	Steel (tn)	Al-PV mount (tn)	Al-PV frame (tn)	Al-Total (tn)	Glass (tn)	Cu-PV cables (tn)	Cu-DC connect (tn)	Cu-Total (tn)	EVA (tn)	Solar cells (tn)	Tedlar (tn)	Potting compound (tn)	Inverter (MW)
2029	86	157	*80*	*9*	89	65	*0.5*	*0.3*	0.8	6	3	3	1	0.84
2030	3,213	5,861	*2,963*	*336*	3,299	2,427	*18.5*	*11.3*	29.8	214	104	119	38	31.40
2031	2,627	4,793	*2,423*	*275*	2,698	1,985	*15.2*	*9.2*	24.4	175	85	98	31	25.68
2032	1,642	2,995	*1,514*	*172*	1,686	1,241	*9.5*	*5.8*	15.2	109	53	61	19	16.05
2033	374	683	*345*	*39*	384	283	*2.2*	*1.3*	3.5	25	12	14	4	3.66
2034	–	–	–	–	–	–	–	–	–	–	–	–	–	–
2035	–	–	–	–	–	–	–	–	–	–	–	–	–	–
2036	452	0	*450*	*47*	497	341	*2.6*	*1.4*	4.0	30	15	17	5	4.41
2037	980	0	*977*	*103*	1,079	741	*5.7*	*3.1*	8.8	65	32	36	11	9.58
2038	294	0	*293*	*31*	323	222	*1.7*	*0.9*	2.6	20	9	11	3	2.87
Total	**9,667**	**14,489**	*9,044*	*1,011*	**10,055**	**7,305**	*55.8*	*33.3*	**89.1**	**643**	**312**	**359**	**113**	**94.50**

TABLE V. AMOUNT OF WASTE MATERIALS FOR TOTAL PV INSTALLATIONS IN GREECE

Year	PV weight (tn)	Steel (tn)	Al-PV mount (tn)	Al-PV frame (tn)	Al-Total (tn)	Glass (tn)	Cu-PV cables (tn)	Cu-DC connect (tn)	Cu-Total (tn)	EVA (tn)	Solar cells (tn)	Tedlar (tn)	Potting compound (tn)	Inverter (MW)
2028	1,140	2,080	*1,052*	*119*	1,171	862	*7*	*4*	11	76	37	42	13	11.15
2029	4,130	7,535	*3,809*	*432*	4,241	3,121	*24*	*15*	38	275	133	153	48	40.37
2030	14,961	27,295	*13,798*	*1,565*	15,363	11,305	*86*	*53*	139	994	483	556	175	146.25
2031	35,652	65,044	*32,881*	*3,729*	36,610	26,939	*206*	*127*	332	2,370	1,150	1,324	418	348.50
2032	74,750	136,375	*68,941*	*7,818*	76,760	56,483	*431*	*267*	698	4,969	2,411	2,777	877	730.69
2033	95,753	174,694	*88,312*	*10,015*	98,328	72,353	*552*	*343*	895	6,365	3,089	3,557	1,123	936.01
2034	–	–	–	–	–	–	–	–	–	–	–	–	–	–
2035	1,133	0	*1,129*	*118*	1,247	856	*7*	*4*	10	75	37	42	13	11.07
2036	8,574	0	*8,545*	*897*	9,442	6,479	*49*	*27*	77	570	277	318	101	83.81
2037	20,620	0	*20,550*	*2,157*	22,707	15,581	*119*	*64*	183	1,371	665	766	242	201.56
2038	7,695	0	*7,669*	*805*	8,474	5,814	*44*	*23*	68	511	248	286	90	75.22
Total	**264,408**	**413,023**	*246,687*	*27,656*	**274,342**	**199,792**	*1,525*	*926*	**2,451**	**17,576**	**8,529**	**9,822**	**3,102**	**2,584.63**

VI. Conclusion

PV installations in Crete and Greece are expected to produce large amount of wastes in the period 2028-2038. In order to manage these wastes, several PV recycling plants have to be installed in Greece. Their number, location, and functional characteristics have to be decided after careful examination. Moreover, it has to be noted that this period (end of March 2014) a new law has been passed that reduces significantly FiTs of PVs. Moreover, this law suggests optional extension of all PV contracts for 7 years with very low FiTs for this additional period, which makes the choice of this option doubtful. As a result, the next step of this analysis will include the consideration of alternative scenarios regarding the period of PV recycling.

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