only electricity consuming equipment" whilst PV modules would fit better in a separate EPR-legislation whether or not together with other Renewable Energy Equipment;

- o The IPPC-Directive which is the basis for any permit or license to operate for any business as well for any waste treatment activity where the key elements are to have at the end an Integrated Pollution Prevention Control for any commercial and industrial activity towards emissions to water, air and soil.

- In both regions, PV modules are considered as "one product, one equipment" – one does not apply a waste law to "components" of an equipment. For example, a junction box, cables of a PV module are all an integrated part of a PV installation and thus the applicable waste laws apply to PV modules. An inverter is an inverter. A battery is a battery.

- In the waste and recycling management industry, one talks about "materials" such as ferro or non-ferro metals, HDPE-plastics or LDPE-plastics etc, glass cullets and the like.

- Most importantly, whereas PV modules and inverters are under the scope of the EU WEEE Directive, the Indian E-Waste (Management and Handling) Rules are not applicable to PV modules and inverters because these E-Waste Rules only apply to two e-waste categories (i) IT and telecommunication equipment and (ii) consumer electronics. Legal-technically an inverter falls under the Indian definition of E-waste but an inverter does not fall under the scope of e-waste because the scope only covers two categories of electrical and electronic equipment whilst in the EU there is an so-called "open scope" whereby each electrical and electronic equipment falls under the scope of the WEEE Directive since August 2018.

- Both the European WEEE Directive and the Indian E-Waste Rules are based on the Extended Producer Responsibility (EPR) principle, foresee mandatory collection targets and are mainly focused on "consumer electronic waste'.

- There are comprehensive Industrial Solid Waste Rules in place in India, but they do not include solar PV within their scope, whilst the European Union has its Waste Framework Directive which settles the basis requirements for each waste type irrespective of Extended Producer Responsibility legislation or other specific legislation which might come on top.

- Crystalline silicon PV modules are not considered as hazardous waste under the Indian Hazardous and Other Waste Rules. While in 2019 MNRE issued a draft blueprint addressing the potential issue of antimony leaching from landfilled solar glass, leaching of antimony from solar glass would occur only in a worst-case end-of-life management scenario in which modules are dumped in an uncontrolled landfill and the solar glass is completely crushed. However, even in this scenario antimony concentration would be significantly below the threshold set by the Hazardous and Other Waste Rules. A ban on landfilling PV modules would virtually eliminate the risk of leaching of antimony and other substances.

- Lead acid batteries are covered by the current Batteries Rules (2001) and Lithium ion batteries are covered by the recent published draft Batteries Rules (2020).

2.4. Recommendations

Looking at the current policy framework around end-of-life PV products in India, preliminary findings show that the following measures should be explored[18]:

- Impose a landfill ban for solar PV modules;
- Implement a legislative framework for voluntary or mandatory Extended Producer Responsibility for equipment coming from the Renewable Energy Industry because the majority of its activities are Business-to-Business (B2B) whereby the industry proposes through a five years management plan its objectives and how to achieve these under supervision if the MNRE and/or MOEF. One of the elements which shall be taken into account is the draft blueprint of the MNRE related solar modules with antimony-containing glass (SPACG).
- A self-standing EPR legislation for PV modules should be created separately from the E-Waste Rules. As PV technology, which is outside the scope of the E-Waste Rules, will become the cornerstone of the energy transition, it is recommended to set out a separate legislation instead of adapting rules from the E-Waste Rules legislation.
- Allow the Indian PV industry to propose a sustainable and long-term solution for the waste generated by a PV system taking into account that PV modules have a very long lifetime and today's generated waste is by far not attractive to enable big industrial waste treatment capacity for PV modules.

It recommended to develop a separate piece of legislation in India to make sure PV modules (and other equipment of a PV system) follow the Ecodesign rules, are adequately collected, treated and financed.

The development of such a piece of legislation can be supported by the current study taking into economic, technological, social and environmental characteristics of India including:

- Technologies for material recovery[19]
- Collection and recycling business models (deposit systems, subsidy systems etc.)
- Recycling fees and cost implications for electricity costs and Indian solar businesses
- Implementation roadmap

---

[19] *While an overview of the available technologies for material recovery is outside the scope of this study, it is relevant to highlight that the environment around the development of PV module recycling technology from the perspective of both the private and public sectors has gained significant traction in the recent years. IEA-PVPS study End-of‐Life Management of Photovoltaic Panels: Trends in PV Module Recycling Technologies (2018) reported 178 PV recycling patents had been filed. Of those, 128 focused on c-Si technology and another 44 were for compound technologies, including thin-film modules.*

Once this preparatory study has been conducted, a separate piece of Indian legislation for the end-of-life management of PV modules should be developed. The new legislative framework should include in the scope inverters and other PV system components. While it is too early to determine whether inverters and other PV components should be part of the same legislation for PV modules or rather be part of the E-Waste Rules, it will be key to ensure synergies across the different pieces of legislation and to optimise the economic, social and environmental dimensions in waste collection and treatment.

The Indian PV recycling legislation could be inspired by lessons learned in Europe. Therefore, it is important to remember that the European WEEE Directive (similar to its Indian counterpart) is legislation, which was originally established for purely household appliances and consumer electronics. The WEEE legislation is not specifically designed for PV appliances or commercial or industrial electrical and electronic equipment. Differences include the following:

- Traditional EEE appliances consume electricity rather than generating electricity;
- Traditional EEE appliances are consumer goods, whereas PV systems and their accompanying equipment (PV modules, inverters, batteries) part of a long-term investment and part of a sustainable energy policy mix;
- Traditional EEE appliances are daily in physical contact with consumers, which is not the case for the equipment of PV systems.

Therefore, it is recommended to invite first the Indian PV Industry to propose a management plan for the end-of-life phase of their products such as PV modules, inverters and batteries, to allow its assessment by the MNRE and to conclude based upon the accompanying discussions if and how legislative support would benefit for the Indian society.

CHAPTER 03

PV WASTE GENERATION SCENARIOS IN INDIA

3.1. Key Findings

The prodigious penetration of PV technology and Balance of Systems (BOS) equipment shall generate at one point in time post-consumer waste. The solar PV modules are considered to be durable and would generally last 30 years or even more. Thus currently, PV module waste generation is not significant considering that only 570.000 tons of PV modules have been installed before the end of 2016. The vast majority of PV modules – 2.175.000 tons – was installed in the period 2017-2019.

PV module waste is not only generated after the end-of-life of the PV module. The origin of PV module waste consists of several types:

- Damaged PV modules during transportation;
- Damaged PV modules during installation;
- Damaged PV modules due to bad weather conditions;
- Damaged PV modules due to a technical failure in the first year(s) of their life; and
- End-of-life or end-of-use PV modules after 30+ years.

Besides post-consumer waste, an additional waste stream is constituted by waste generated in the manufacturing phase. However, as this study looks at post-consumer waste, the waste generated during manufacturing has not been taken into consideration.

The biggest share of PV modules waste is accounted for by the end-of-life (EoL) discarded PV modules. EoL modules will constitute by far and large the main source of PV waste in the long run; however, considering the 30 years lifetime, the waste streams deriving from EoL PV modules will become significant only in the early 2040s. Before this period, this waste amount will be negligible.

However, in order to understand the amount of PV modules waste flows in the coming decades, it is important to consider non-EoL-waste flows. This will contribute to a sustainable energy economy and to prevent adverse environmental and economic impacts which could arise from the wrong practices of disposal of PV modules and their components.

A three-step approach was undertaken to project the PV waste that will be generated in India by the year 2030. Firstly, the annual and cumulative growth of the installed PV capacity in India has been estimated under three scenarios. In addition, a number of assumptions have been made with regard to PV module weight, PV annual replacement rates, and PV modules damaged during transportation and construction. Based on these scenarios, the mass of PV waste generated due to early failures or damages (i.e., during transportation, installation and operation) was derived.

According to the analysis carried out in the context of this study, by the year 2030 India will generate a cumulative mass of PV module waste of 11 kilo tonnes (kt) in the Low scenario, 21 kt in the Medium scenario, and 34 kt in the High scenario. The waste generated due to the end of life of the PV modules would start accumulating only around after the year 2040 and will become rapidly the most relevant waste source.

Table 1 - Total mass of PV waste, annual (kt). Source: own elaboration.

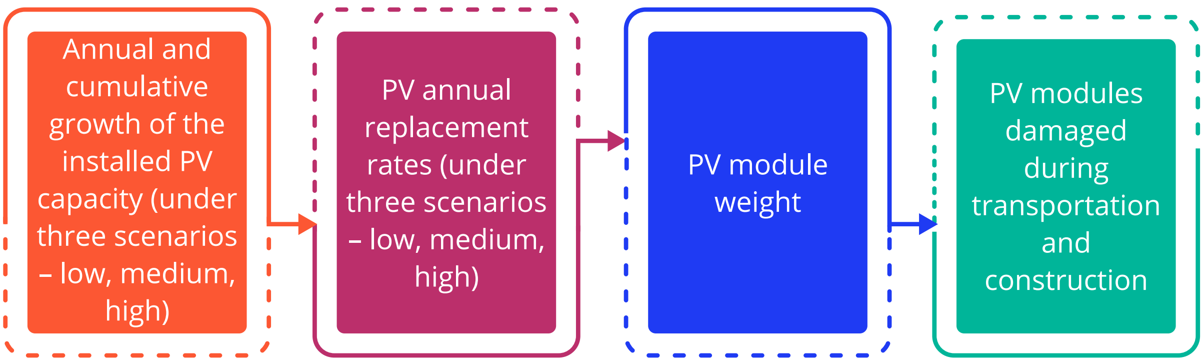
	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Low scenario	0,8	0,8	1,0	1,0	1,0	1,1	1,2	1,3	1,4	1,5
Medium scenario	1,4	1,5	1,5	1,4	1,6	1,9	2,2	2,6	3,1	3,6
High scenario	1,8	4,7	4,9	4,8	4,5	4,0	3,4	2,8	2,1	1,5

Table 2 - Total mass of PV waste, cumulative (kt). Source: own elaboration.

	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Low scenario	0,8	1,6	2,6	3,6	4,6	5,7	7,0	8,3	9,7	11,2
Medium scenario	1,4	2,9	4,5	5,8	7,4	9,3	11,5	14,2	17,2	20,8
High scenario	1,8	6,5	11,4	16,2	20,7	24,8	28,2	31,0	33,1	34,6

3.2. Waste generation assumptions and scenarios

To calculate waste generation over the next decade we have made a few consequential assumptions regarding:



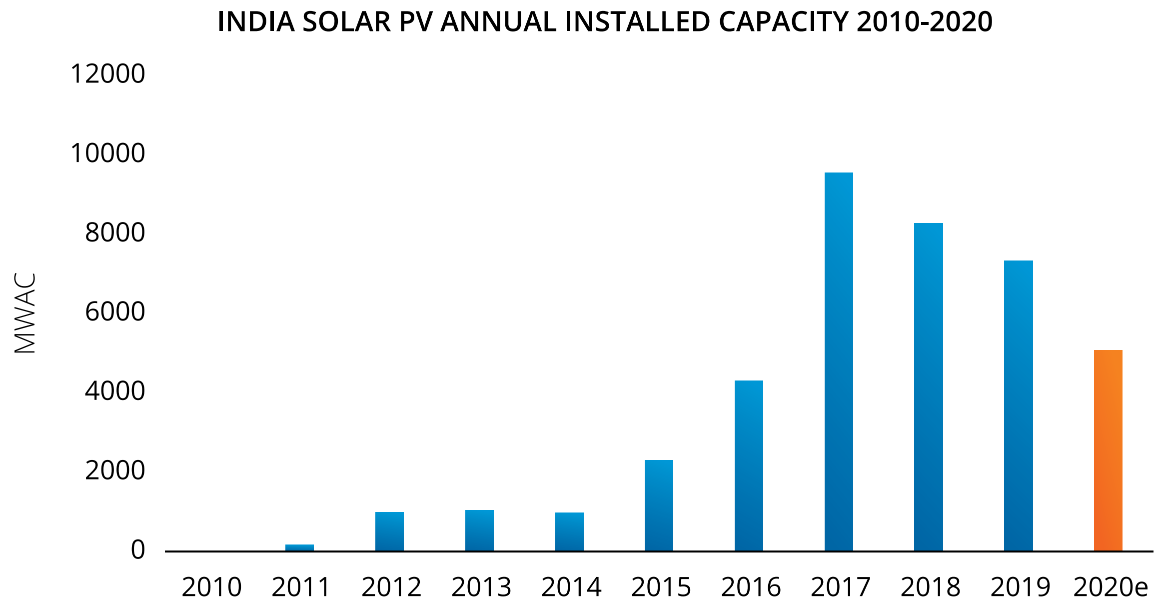
3.2.1. Historical data

The PV capacity annually installed in India from 2010 to 2020, expressed in GWAC and considering the calendar year, is shown in the figure below, based on NSEFI and SolarPower Europe data and 2020 estimate.

Table 3 - Annual installed PV system capacity from 2010 to 2020. Source: NSEFI and SolarPower Europe (2020).

	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020e
MWAC	12	177	998	1044	984	2313	4313	9558	8286	7340	5083

Figure 2 - Annual installed PV system capacity from 2010 to 2020. Source: NSEFI and SolarPower Europe (2020).



It can be noted that the PV market effectively started in 2012, and boomed only in 2016-17. No significant amounts of EoL PV modules shall therefore be expected before 2042.

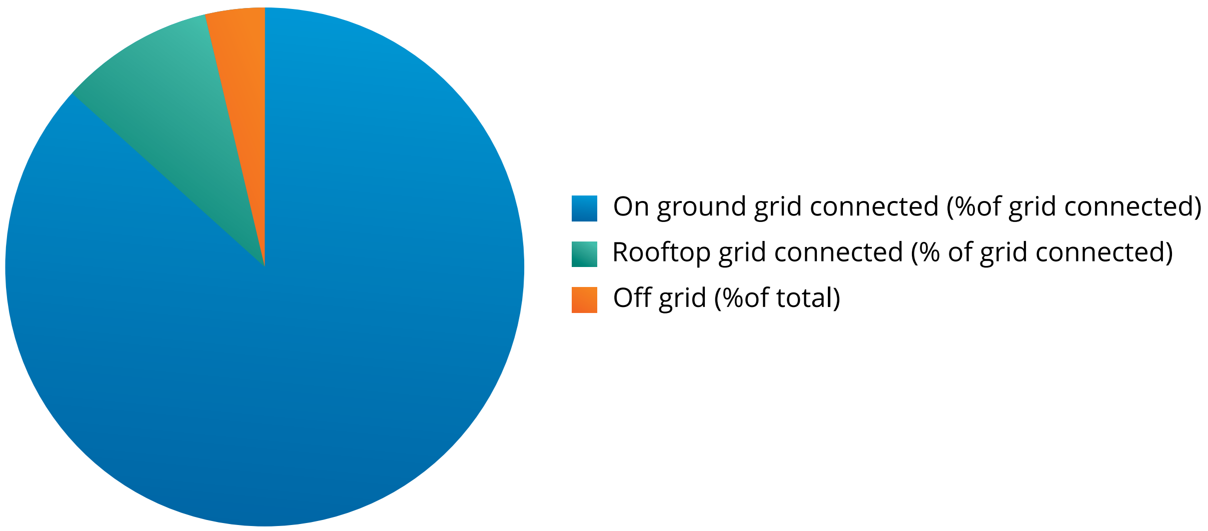
3.2.2. Assumptions related to the market share

The projections cover the sectoral market breakdown, it is assumed that 90% of the market of grid-connected systems belonged to the ground-mounted plants and 10% of the market was taken by the rooftop or small-scale PV rooftop systems. The share of the off-grid systems till 2020 is negligible, at the 2% - 3% level of the total market share.

Table 4 - Year-wise sectoral breakdown of PV systems capacity. Source: Own elaboration.

MWAC	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020e
Annual total capacity	12	177	998	1044	984	2313	4313	9558	8286	7340	5083
Ground-mounted %	90%	90%	90%	90%	90%	90%	90%	90%	90%	90%	90%
Ground-mounted capacity	11	159	898	940	886	2082	3882	8602	7457	6606	4575
Rooftop %	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%
Rooftop capacity	1	18	100	104	98	231	431	956	829	734	508
Cumulative capacity	12	189	1187	2231	3215	5528	9841	19399	27685	35025	40108

Figure 3 - Breakup of the installed PV capacity for 2019. Source: PV Rooftop Cell.



Commercial installations shared the majority of the PV rooftop systems (the detailed breakdown in not available in the literature). Given that ground-mounted solar constitutes the vast majority of PV capacity, and that the residential segment is only a fraction of rooftop installations, it can be concluded that the greatest bulk of end-of-life PV waste will be deriving from B2B relations. A B2B network for end-of-life management of PV waste would be the preferred choice to address this.

3.2.3. Assumptions related to the annual growth of PV generation capacity

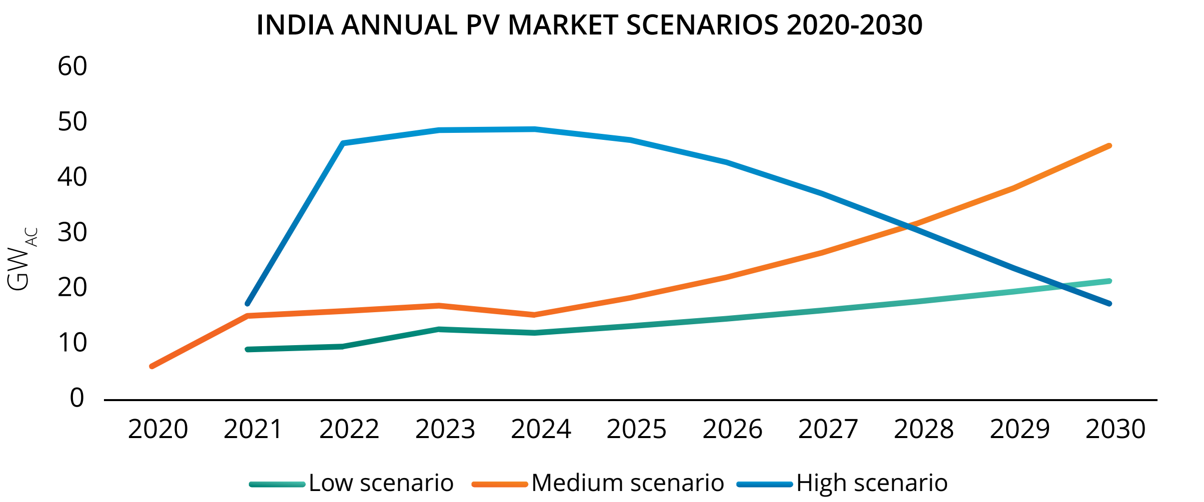
The three scenarios (Low, Medium, High) of the growth of the installed PV capacity are shown below. The Low and Medium scenarios are based on SolarPower Europe's Global Market Outlook 2020-2024 forecasts, and assume an annual growth post-2024 of 10% and 20% respectively. For the High scenario it is assumed a very steep growth rate in 2021 and

2022 taking into account the India's National Solar Mission goals (by 2022 100 GW of solar PV systems are proposed to be installed). The High scenario leads to the achievement of the 400 GW PV installation capacity in 2030.

Table 5 – India annual PV market scenarios 2020-2030. Source: Own elaboration, based on SolarPower Europe (2020) and MNRE.

ANNUAL GW	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Low scenario		9,1	9,7	12,8	12,2	13,4	14,7	16,2	17,8	19,6	21,6
Medium scenario	6,1	15,2	16,1	17,1	15,4	18,5	22,2	26,6	31,9	38,3	46,0
High scenario		17,4	46,5	48,8	49,0	47,0	43,0	37,3	30,7	23,9	17,4

Figure 4 - India annual PV market scenarios 2020-2030. Source: Own elaboration, based on SolarPower Europe (2020) and MNRE.

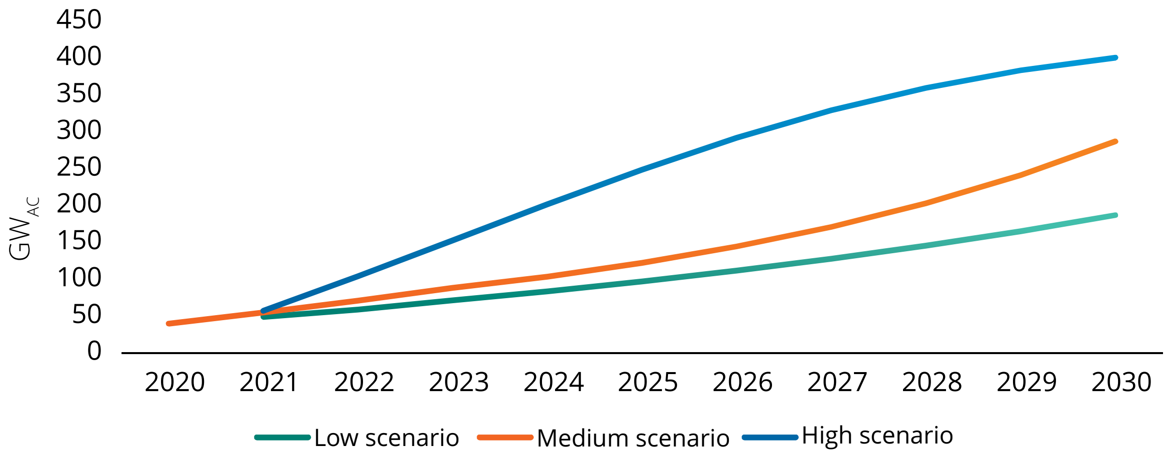


Compared to current levels, the annual PV market is expected to grow significantly across all scenarios. The Low and Medium scenarios forecast a somewhat stable level of annual installations in the next 5 years, between 9 and 18 GW installed annually. In the mid and long term, annual installations increase significantly, reaching 22-46 GW by 2030. Conversely, the High scenario assumes that national government objectives are reached – this causes a surge of installed capacity in 2021 and 2022. After peaking in 2024, annual installations decline and are at 17 GW in 2030. This results in annual installations in the High scenario to become eventually lower than in the other two scenarios, although the cumulative capacity remains significantly higher.

Table 6 - India cumulative PV market scenarios 2020-2030. Source: Own elaboration, based on SolarPower Europe (2020) and MNRE.

CUMULATIVE GW	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Low scenario		49,2	58,9	71,7	83,8	97,2	111,9	128,1	145,9	165,5	187,1
Medium scenario	40,1	55,3	71,4	88,5	103,9	122,3	144,5	171,1	203,1	241,4	287,4
High scenario		57,5	104,0	152,8	201,8	248,9	291,9	329,2	359,9	383,8	401,2

Figure 5 - India cumulative PV market scenarios 2020-2030. Source: Own elaboration, based on SolarPower Europe (2020) and MNRE.



By 2030, cumulative installed capacity experiences a multi-fold growth across all scenarios. Under the Low and Medium scenarios cumulative capacity reaches 187 and 287 GW respectively, up from 40 GW in 2020. The High scenario capacity reaches 400 GW by 2030, in line with government ambition.

Assuming that PV systems installed in 2020-2030 have a lifetime of at least 30 years, any capacity installed during this period will reach the end-of-life stage not before 2050.

3.2.4. Assumptions related to the PV waste components

We can assume that till 2035 the main waste will be generated during transportation, installation or operation due to damages or early failures. Main waste components will be PV modules, whereas inverters have much lower mass. Other components like ballasts, mounting structures, wires, and other BoS are less likely to be subject to damage and early failure.

3.2.5. Assumptions related to the rate of transportation and installation damage

Even with careful transportation of solar modules, there are damages to PV modules; this phenomenon can be called as the "transportation damage". It is assumed that the transportation damage can be detected before or during the PV module installation, therefore before the start of the product lifetime. The transportation loss can occur on all transportation stages: packaging, transfer to the ship, marine shipment, transfer to trucks, during the road transportation, unpacking, etc.

The failure may also be caused during the installation of the PV system which may ultimately result in generation of PV waste.

We asked the module manufacturers and developers about the most probable value of the damage. The respondents claimed that the transportation damage is lower than 0.1% in 2020. Based on the inputs received from the stakeholders, it is assumed that the rate of transportation and installation damage is 0.1%.

3.2.6. Assumption of the weight (mass) of solar modules

It is assumed that for 2020 average mass of 1 MW of solar modules is around 65 kg and the weight includes frames; however, it does not include wires, mounting structures, inverters, ballasts etc. For the final calculation, additional assumption of the additional mass should be taken into account (inverters might contribute to the waste stream, but their addition would be negligible compared to PV module waste).

Table 7 - Assumption of 1 MW PV module waste 2010-2020. Source: SolarPower Europe, PV CYCLE and NSEFI estimate.

	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
t	100	96	92	88	85	82	78	75	72	69	65

Table 8 - Assumption of 1 MW PV module waste 2021-2030. Source: SolarPower Europe, PV CYCLE and NSEFI estimate.

	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
t	65	64	62	61	60	59	58	56	55	54

3.2.7. Assumption of the annual replacement rate

The values of the "replacement rate" are discovered during the interviews carried out by the EU– India TC Project with the representatives of installers and vendors. The above-mentioned value will be reconsidered in the subsequent stages as per the inputs received from the stakeholders.

Table 9 - Annual replacement rate scenarios. Source: Interviews with the Indian installers.

Annual replacement rate (%)		
Low scenario	Mid scenario	High scenario
0,03%	0,045%	0,06%

3.3. Calculations

3.3.1. Calculation of the mass of the installed capacity

The mass of the installed modules is calculated as follows:

Table 10 - Annual PV module mass (kt). Source: own elaboration.

ANNUAL (kt)	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Low scenario	593	615	798	744	802	865	932	1005	1084	1168
Medium scenario	988	1026	1064	942	1108	1303	1532	1802	2119	2492
High scenario	1131	2962	3047	3000	2820	2526	2150	1733	1319	943

Table 11 - Cumulative PV module mass (kt). Source: own elaboration.

CUMULATIVE (kt)	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Low scenario	3199	3751	4474	5129	5828	6577	7378	8235	9154	10139
Medium scenario	3595	4548	5522	6353	7334	8490	9853	11458	13348	15573
High scenario	3737	6624	9539	12348	14921	17149	18956	20310	21223	21742

3.3.2. Calculation of the waste generated during transportation and installation

Waste generated during the transportation and installation is as follows:

Table 12 - Mass of PV module waste generated during transportation (kt). Source: own elaboration.

ANNUAL (kt)	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Low scenario	0,6	0,6	0,8	0,7	0,8	0,9	0,9	1,0	1,1	1,2
Medium scenario	1,0	1,0	1,1	0,9	1,1	1,3	1,5	1,8	2,1	2,5
High scenario	1,1	3,0	3,0	3,0	2,8	2,5	2,2	1,7	1,3	0,9

3.3.3. Calculation of the waste generated during operation

Waste generated during operation is as follows:

Table 13 - Mass of PV module waste generated during operation (kt). Source: own elaboration.

ANNUAL (kt)	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Low scenario	0,2	0,2	0,2	0,2	0,2	0,3	0,3	0,3	0,3	0,4
Medium scenario	0,4	0,5	0,5	0,4	0,5	0,6	0,7	0,8	1,0	1,1
High scenario	0,7	1,8	1,8	1,8	1,7	1,5	1,3	1,0	0,8	0,6

3.3.4. Calculation of the total waste generated from new installations

The total mass of waste generated from new installations is as follows:

Table 14 - Total mass of PV module waste from new installations, annual (kt). Source: own elaboration.

ANNUAL (kt)	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Low scenario	0,8	0,8	1,0	1,0	1,0	1,1	1,2	1,3	1,4	1,5
Medium scenario	1,4	1,5	1,5	1,4	1,6	1,9	2,2	2,6	3,1	3,6
High scenario	1,8	4,7	4,9	4,8	4,5	4,0	3,4	2,8	2,1	1,5

Table 15 - Total mass of PV module waste from new installations, cumulative (kt). Source: own elaboration.

CUMULATIVE (kt)	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Low scenario	0,8	1,6	2,6	3,6	4,6	5,7	7,0	8,3	9,7	11,2
Medium scenario	1,4	2,9	4,5	5,8	7,4	9,3	11,5	14,2	17,2	20,8
High scenario	1,8	6,5	11,4	16,2	20,7	24,8	28,2	31,0	33,1	34,6

Overall, it can be observed that total PV waste forecast from new installations deriving from transportation, installation and operation is relatively small. Annual waste does not exceed 2 kt in the Low scenario and stays below 4 kt in the Medium scenario. The High scenario anticipates a ramp up of installations in 2022 that results in 4,7-4,9 kt annually between 2022 and 2024. In cumulative terms, the total mass of PV module waste deriving from transportation, installation and operation reach 11, 21 and 35 kt in the Low, Medium and High scenario respectively.