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Accident risk assessment for Solar Photovoltaic manufacturing

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In the broader context of the energy transition and the goal to achieve net-zero greenhouse gas emissions by 2050, it is of major interest to have a comparative perspective on risks related to accidents for a broad range of energy technologies. This is an essential contribution to support stakeholders in complex decision-making processes to plan, design and establish supply chains that are economic, efficient, reliable, safe, secure, and sustainable. Among renewable technologies, solar photovoltaic (PV) is expected to be a major contributor. Therefore, this study presents a first step on the assessment of accident risk considering a full-chain perspective for current and future PV technologies to be included in a comparative assessment for energy technologies. In particular, it focused on the comparative accident risk assessment for PV manufacturing. Designated hazardous substances involved in PV manufacturing chains are selected from life cycle inventories to characterize the risk of PV production processes. The assessment quantitatively estimated the accident risk of hazardous substances with risk indicators, e.g., fatality rate, using global historical data collected from multiple industrial accident databases. The hazardous substances risk indicators are allocated to the PV technologies to estimate manufacturing accident risk, and to compare their relative contributions to overall PV indicators. Results indicate that hydrochloric acid, hydrofluoric acid, and sodium hydroxide are the most significant hazardous substances. Furthermore, among the considered PV technologies, results reveal that copper-indium-gallium-diselenide (CIGS) panels have the worst risk performance compared to the other technologies, while cadmium telluride (CdTe) panels performed best.

Keywords: Risk Assessment, Solar Photovoltaic, Manufacturing, Accidents, Hazardous Substances, ENSAD

1. Introduction

The energy sector is at a critical transition point considering the Paris Agreement and the necessary reduction in global greenhouse gas emissions (IPCC 2018). In this context, the deployment of renewable energy technologies is considered a key path to the decarbonization of the energy sector (IRENA 2019). Among the available technologies, solar photovoltaic (PV) is expected to be a major contributor among renewables and currently accounts for 63% of new renewable installed capacity (Masson and Kaizuka 2020).

High costs were previously a barrier to deployment, but technical advances in manufacturing in recent years have resulted in considerable cost reductions improving the competitiveness of solar PV with conventional energy technologies (Woodhouse et al. 2019).

Beyond direct comparisons of cost and emissions between energy technologies, it is of major interest to have a comparative perspective addressing risk related to accidents for a broad range of energy technologies This is useful in evaluating safety performances and to rank the energy systems under consideration, which can have important implications on the environmental (e.g. land and water contamination), economic (e.g. property damage, business interruption) and social (e.g. human health impacts) dimensions of sustainability.

Furthermore, comparative accident risk assessment and the calculation of transparent and consistent risk indicators is an essential contribution to support stakeholders in complex decision-making processes to plan, design and establish supply chains that are economic, efficient, reliable, safe, secure, and sustainable (Burgherr and Hirschberg 2014).

In the literature accident risk for PV are particularly focusing on installation (e.g., working at height with risk of falls, exposure to adverse weather, etc.) and operational accidents (e.g., fire with potential release of toxic hazardous substances, etc.) (NSW 2021; Moser et al. 2016).

However, taking a full chain perspective, manufacturing of a PV panel is also source of potential accidents with effects on the human health due to the use of hazardous substances (Fthenakis et al. 2006). In the literature, accident risk in the PV manufacturing chain has been barely studied (Zapata Riveros 2010), since the research focused on the toxicity assessment for specific hazardous substances (Ramírez-Márquez et al. 2020), but it is now considered outdated due to the rapid technological improvements in recent years (Frischknecht et al. 2020).

Based on these premises, this study presents a first step on the assessment of accident risk considering a full-chain perspective for current and future PV technologies to be included in a comparative assessment for energy technologies. In particular, it focused on the comparative accident risk assessment for PV manufacturing. Based on this premise, this study aims to answer the following questions:

- What are the most hazardous substances in the PV manufacturing?
- What are the riskier PV technologies in the manufacturing context?

To answer these questions, first, an overview of PV technologies and the hazardous substances used during manufacturing is given (section 2). Afterwards, the accident data related to the selected hazardous substances employed in the manufacturing of PVs are collected and presented (section 3). In section 4, the method implemented in this study for the accident risk assessment is presented. Finally, in section 5, the comparative accident risk assessment is shown.

2. Overview of Solar Photovoltaic (PV)

2.1. PV Technologies

Solar photovoltaic technologies convert sunlight into electricity using semiconducting materials. They function based on the photovoltaic effect in which absorbed photons from sunlight provide energy to release electrons from their bound position in the semiconductor by overcoming the band-gap energy required for excitation. The generated electron-hole pairs are charge carriers and are separated by a potential barrier to avoid recombination (Markvart and Castaner 2018).

The typical semiconducting material used for PV technologies is silicon. The silicon is normally doped with boron and phosphorous to create n-type and p-type crystals which allow for the free movement of electrons and holes. The p-n junction of the doped silicon crystals creates the potential barrier that separates the electron-hole pairs (Markvart and Castaner 2018). The silicon is used to create solar cells which are manufactured together with electrical equipment and protective layering to produce a PV panel or module capable of producing power at useful scales. Although silicon is the most common semiconducting material used for PV panels, there are a range of other materials that can also generate electricity using the photovoltaic effect.

Photovoltaic technologies are generally classified into three categories including wafer-based cells, commercial thin-film, and emerging thin-film cells. Wafers designate a thin slice of semiconducting material while thin-film technologies refer to the deposition of semiconducting films onto a substrate. Crystalline silicon (c-Si) is the traditional wafer-based technology separated into monocrystalline silicon (mono-Si) and multicrystalline silicon (multi-Si). Gallium arsenide (GaAs) is an additional notable wafer-based technology (Kearney ETI 2017). Amorphous silicon (a-Si), cadmium telluride (CdTe), and copper-indium-gallium-diselenide (CIGS) are designated as commercial thin film technologies (Kearney ETI 2017). The range of emerging thin film technologies includes perovskite, dye-sensitized solar cells (DSSC), organic PV (OPV), copper-zinc-tin-sulfide (CZTS), and quantum dot (QDPV) (Kearney ETI 2017).

Solar PV technology has grown rapidly in recent years driven by remarkable cost reductions due to technical advances in manufacturing processes and panel conversion efficiencies (Woodhouse et al. 2019).

2.2. Hazardous Substances in PV Manufacturing

This study focuses on the accident risk during manufacturing of the most relevant PV technologies that are either commercially available or developing with a strong potential for competitive implementation in the future. Based on these premises, the following PV technologies are considered:

- mono-Si and multi-Si, since crystalline silicon is the traditional photovoltaic technology and accounted for 95% of total production in 2020 (Fraunhofer ISE 2021);
- CdTe and CIGS cover a significant market share of the thin-film technologies, which accounted for 5% of total capacity in 2020 (Taylor and Jäger-Waldau 2020);
- Tandem perovskite/Si, which is still an emerging technology, has a high potential to complement existing commercial technologies due to the flexibility of perovskite and its capability for band gap tuning that can improve the conversion efficiency of tandem cells above 29% (Masson and Kaizuka 2020; Taylor and Jäger-Waldau 2020).

For each of the selected PV technologies, the most hazardous substances involved in production processes within the manufacturing chain are considered. The list of hazardous substances is retrieved from the primary technosphere inputs listed in the Life Cycle Inventory (LCI) developed for the Life Cycle Inventories and Life Cycle Assessments of Photovoltaic Systems report by the IEA Photovoltaics Power Systems Program (PVPS) (Frischknecht et al. 2020) and the major intermediate by-products chemicals obtained from analysing the manufacturing process. The substances are selected if a severe hazard rating is identified for health, flammability, and reactivity in hazardous substance fact sheets. Although toxicity is outside the scope of the assessment, the sources of extreme toxicity are partially accounted for through the inclusion of lead and cadmium in the hazardous substance list which are the substances of greatest concern for toxic release from PV panels (Sinha et al. 2019).

The list of selected primary and supplementary hazardous substances is provided in Table 1 along with the main hazards of each hazardous substance.

3. Data

In this study, historical accidents related to the use of hazardous substances causing at least one type of consequence (e.g., 1 fatality, 1 injury, etc.), are collected for the time 2000-2020 worldwide. The PV production capacity has increased steadily from 2000 to 2020 with most of the production occurring after 2005.

Table 1: List of identified hazardous substances in PV manufacturing

Hazardous Technosphere Inputs	Hazard Summary
Ammonia (NH_3)	Toxic, corrosive, flammable
Cadmium (Cd)	Carcinogen, toxic
Diborane (B_2H_6)	Flammable, explosive, toxic
Hydrochloric Acid (HCl)	Corrosive
Hydrofluoric Acid (HF)	Corrosive, toxic
Hydrogen	Flammable, explosive
Hydrogen Sulfide (H_2S)	Toxic, flammable
Lead (Pb)	Carcinogen, toxic
Nitric Acid (HNO_3)	Corrosive, toxic, reactive
Phosphoryl Chloride ($POCl_3$)	Corrosive, toxic
Silane (SiH_4)	Flammable, explosive
Sodium Hydroxide (NaOH)	Corrosive
Sulfuric Acid (H_2SO_4)	Corrosive, reactive
Intermediate Hazards	**Hazard Summary**
Boron trichloride (BCl_3)	Corrosive, toxic
Boron trifluoride (BF_3)	Corrosive, toxic
Cadmium (Cd)	Carcinogen, toxic
Hydrogen selenide (H_2Se)	Flammable, explosive
Silicon tetrachloride ($SiCl_4$)	Corrosive, reactive
Trichlorosilane ($SiHCl_3$)	Flammable, explosive
Phosphine (PH_3)	Flammable, reactive

The year 2000 is selected as the cut-off date for historical data to cover the full relevant period of PV manufacturing and to improve the statistical population of accident data, since before 2000 the PV production capacity can be considered insignificant (Fraunhofer ISE 2021).

Previous data collection and analysis for solar PV has focused on the OECD country cluster (Zapata Riveros 2010), but this analysis expands the scope of data collection to cover all accidents occurring globally.

The PV manufacturing occurs primarily in China and the non-OECD country cluster, so a global perspective is necessary for an accurate estimation of manufacturing-related accident risk (Masson and Kaizuka 2020). Although all accidents of varying severity are collected, the process focused on accidents reporting casualties which are the most complete statistics for estimating accident risk (Spada, Sutra, and Burgherr 2021). Fatalities are the most dependable and accurate value and is the most rigorously applied filter criteria for data collection. Injuries are an important collection filter as well but are subjective compared to fatalities and range from serious injury requiring hospitalization to being inconvenienced, irritated, or affected. All chain stages from production to disposal for each hazardous substance are collected to include as much information as possible.

In this study, different industrial accident databases are surveyed to find information about accidents related to the use of hazardous substances. Finally, the collected data are homogenized prior to analysis, to avoid possible double counts. The examined databases are the Analysis Research and Information on Accidents (ARIA) database , the Failure and Accidents Technical Information System (FACTS), the National Response Center (NRC) database, and Hazards Intelligence (HINT), which was an international journal published by Ility Engineering in Finland that contains industrial incidents from 2000 to 2014. The summary of the collected accident data worldwide for the hazardous substances listed in Table 1 are presented in Table 2. It is important to note that limited accident data were found for some hazardous substances in Table 1, and therefore they are not considered further in this study.

4. Method

4.1. Overview

Risk can be decomposed into the product of the frequency and severity (Haimes 2009). The frequency is the number of accidents over a certain period and the severity is the degree of consequences represented by fatalities, injuries, monetary loss, etc. (Burgherr and Hirschberg 2014).

Table 2: Summary of accidents related to the use of hazardous substances with at least 1 consequence (e.g., 1 fatality) in the time range 2000-2020

Hazardous Substance	Immediate Fatalities	Immediate Injuries
	Acc/Fat	Acc/Inj
Ammonia	132/1136	772/7999
Hydrochloric Acid	25/45	140/1168
Hydrofluoric Acid	11/17	65/3386
Hydrogen	58/125	101/499
Hydrogen Sulfide	117/535	158/22230
Lead	4/11	49/8530
Nitric Acid	15/25	118/752
Sodium Hydroxide	23/59	170/2289
Sulfuric Acid	58/772	331/2280

To assess the risk, the standard historical based approach to estimate aggregated indicators (e.g., fatality rates, injury rates) is applied. The latter are given by the ratio of the sum of fatalities/injuries in the period under interest (2000–2020) and the total production (e.g., kWh, GWeyr, etc.) in the same period. These provide a measure of expected fatalities/injuries per unit of energy produced, i.e., the average risk (Spada, Sutra, and Burgherr 2021). The sum of fatalities/injuries are defined in section 3. On the other hand, the assessment of the normalisation factor in unit of electricity produced, Gigawatt-electric-year (GWeyr), is described in section 4.2, since the PVs manufacturing is not directly related to the electricity produced by the panel.

4.2. Normalization

To derive a comparable measure of accident risk for the use of hazardous substances in PV manufacturing, the accident risk indicators are normalized by the energy production in terms of GWeyr (Spada, Sutra, and Burgherr 2021). To assess the normalization factor in GWeyr for each hazardous substance analysed in this study, their use in PV manufacturing relative to total production must be estimated.

To perform this, first the total global production for each hazardous substance is collected to normalize the risk indicators with respect to hazardous substance quantity in kg.

Table 3: Summary of hazardous substance data for total production in the period 2000-2020 and mass usage for PV technologies

Hazardous Substance	Total Production (kg)	Mono-Si (kg/m^2)	Multi-Si (kg/m^2)	CdTe (kg/m^2)	CIGS (kg/m^2)	Tandem Perovskite/Si (kg/m^2)
Ammonia	2.74E+12	2.05E-02	8.34E-03		9.29E-02	2.05E-02
Hydrochloric Acid	4.20E+11	9.22E-01	1.00E+00		9.94E-02	9.22E-01
Hydrofluoric Acid	2.31E+10	6.87E-02	4.39E-01			6.34E-03
Hydrogen	1.05E+12	2.88E-02	3.10E-02			2.88E-02
Hydrogen Sulfide	6.93E+10				1.91E-01	
Lead	8.65E+10	9.68E-04	9.68E-04			2.59E-03
Nitric Acid	1.16E+12	3.83E-02	2.74E-01	5.72E-02		3.83E-02
Sodium Hydroxide	1.47E+12	8.03E-01	2.99E-01	4.93E-02	3.34E-02	8.03E-01
Sulfuric Acid	4.85E+12		9.46E-02	3.93E-02	3.31E-02	

Afterwards, the accident risk indicators in terms of hazardous substance mass are allocated to the PV technologies based on the amount of each hazardous substance used to manufacture a panel in terms of kg/m^2.

Following the allocation of hazardous substance risk to PV, data for module efficiencies and the PV capacity factor are collected to normalize the allocated PV panel risk to the energy produced to be comparable among each other. Annual production quantities for ammonia and lead are collected from mineral commodity statistics provided by the United States Geological Survey (USGS). Annual production estimates for hydrogen, nitric acid, sodium hydroxide, and sulfuric acid utilized the Essential Chemical Industry (ECI). For hydrogen sulfide, an estimate for annual anthropogenic production is used instead of hazardous substance production because anthropogenic production is assumed to encompass the sources of risk more accurately (Watts 2000). Finally, annual production estimates for hydrochloric and hydrofluoric acids are provided by (Lumitos) and (Roberts 2015), respectively (Table 3).

The technosphere input quantities for the hazardous substances are collected from every manufacturing chain stage available in Frischknecht et al. (2020). The technosphere input quantities for each hazardous substance are summed across the entire chain and normalized to panel area to calculate the total mass usage per square meter of the manufactured PV module (Table 3).

To convert the normalisation factor in terms of kg/m^2 to GWeyr, the module efficiencies and the capacity factors for the PV technologies are required. The efficiency provides the rated power capacity/m^2, while the capacity factors provide the conversion from power to electricity generation. In this study, the power capacity in direct current (WDC) per square meter of panel that the module is rated to produce during periods of peak sunlight is given by the product of the panel conversion efficiency (Frischknecht et al. 2020) and the standard test condition (STC) solar irradiance value of 1000 W/m^2 (Table 4).

It is important to note that since the tandem perovskite/Si panels are still under development, the confirmed record efficiency of 29.5% for an Oxford PV tandem cell is used (Fraunhofer ISE 2021). Estimates for perovskite/Si panels are used to examine the potential effects future technologies and improvements to conversion efficiencies can have on reducing the risk of PV, so using a maximum proven efficiency supports the analytical purpose of perovskite/Si technology.

Table 4: Summary of the module efficiency and estimated power capacity per square meter for the selected PV technologies

PV Technologies	Module efficiency (%)	Power Capacity per square meter (WDC/m^2)
Mono-Si	19.5	195
Multi-Si	18	180
CdTe	18	180
CIGS	16	160
Tandem Perovskite/Si	29.5	295

To convert the rated power capacities of the PV technologies to the expected energy production, a capacity factor is required encompassing a variety of PV performance characteristics. The most important aspect is that the rated power capacity assumes operation at standard peak solar radiation with STC conditions which rarely occur under real operating conditions.

The performance is directly influenced by solar irradiance, atmospheric conditions, temperature, and soiling. The other important aspect of the capacity factor is to account for electrical system losses that occur when converting direct current (DC) power to alternating current (AC) power to supply electricity to the grid. Data for the capacity factor encompassing the range of information is collected from ESMAP (2020). The provided capacity factors are converted to an average energy production per year per unit of installed capacity (kWyr/kWDC). From there, a single overall capacity factor of 0.16 kWyrAC/kWDC is estimated based on the weighted average of regional capacity factors using their share of global installed PV capacity. This factor is used for accident risk assessment to normalize rated installed capacity to energy production. Finally, the expected energy production determined using the capacity factor is normalized to the unit of GWeyr.

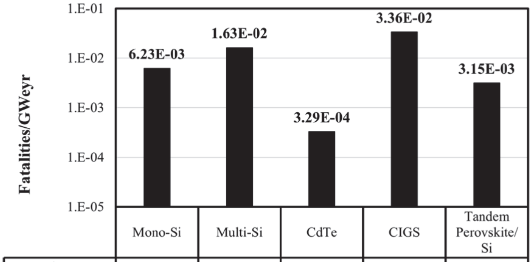
5. Results

In this section, the fatality rate (section 5.1), i.e., the total number of fatalities in Table 2 normalized by GWeyr following the description in section 0, and the injury rate (section 5.2), i.e., the total number of injuries in Table 2 normalized by GWeyr following the description in section 0, for the manufacturing of mono-Si, multi-Si, CIGS, CdTe and Tandem perovskite/Si PV panels are presented.

Furthermore, the results show the contribution of each hazardous substance to the PV accident risk indicator. It is important to note that fatalities and injuries related to hazardous substances used in PV manufacturing refer to immediate casualties, since long-term exposure and toxicity are not considered in this assessment.

5.1. Fatality Rate

Fig. 1 compares the fatality rates for the selected PV technologies.



	Mono-Si	Multi-Si	CdTe	CIGS	Tandem Perovskite/ Si
Ammonia	2.72E-04	1.20E-04		1.50E-03	1.80E-04
Hydrochloric Acid	3.17E-03	3.72E-03		4.16E-04	2.09E-03
Hydrofluoric Acid	1.62E-03	1.12E-02			9.88E-05
Hydrogen	1.10E-04	1.28E-04			7.25E-05
Hydrogen Sulfide				3.14E-02	
Lead	3.95E-06	4.28E-06			6.97E-06
Nitric Acid	2.66E-05	2.06E-04	4.30E-05		1.76E-05
Sodium Hydroxide	1.03E-03	4.16E-04	6.87E-05	5.24E-05	6.83E-04
Sulfuric Acid		5.22E-04	2.17E-04	2.06E-04	

Fig. 1 Fatality rate comparison of PV Technologies, including the contribution of each hazardous substance to the total risk indicator

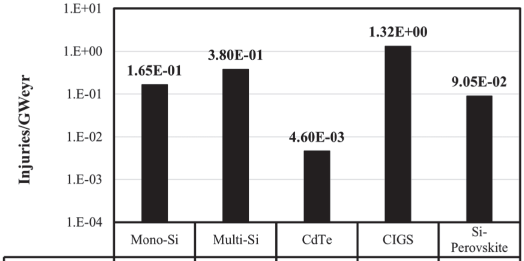
Results show that the CdTe panel production performs best with respect to the other PV technologies. This is related to the low quantity of hazardous substances used in the manufacturing of this panel. Furthermore, among the used hazardous substances, sulfuric acid contributes most to the CdTe fatality rate followed by sodium hydroxide and nitric acid.

On the other hand, CIGS technology performs worst. This effect is due to the estimated extreme risk contribution from hydrogen sulfide followed by ammonia. Mono-Si fatality rate results are lower than multi-Si due to the assumed higher rated conversion efficiency of mono-Si and the larger mass usage of hydrofluoric acid in multi-Si. Furthermore, mono-Si and multi-Si fatality rates are higher than CdTe and tandem perovskite/Si, due to the large risk contribution of hydrochloric and hydrofluoric acid followed by sodium hydroxide and ammonia.

Finally, the tandem perovskite/Si fatality rate results are 45% lower than mono-Si due to its higher assumed conversion efficiency and reduced use of hydrofluoric acid in final panel production. Hydrochloric acid, ammonia, and sodium hydroxide contribute most to the fatality rate for tandem perovskite/Si.

5.2. Injury Rate

Fig. 2 compares the injury rates for the selected PV technologies.



	Mono-Si	Multi-Si	CdTe	CIGS	Si-Perovskite
Ammonia	1.92E-03	8.45E-04		1.06E-02	1.27E-03
Hydrochloric Acid	8.22E-02	9.66E-02		1.08E-02	5.43E-02
Hydrofluoric Acid	3.68E-02	2.55E-01			2.24E-03
Hydrogen	4.38E-04	5.11E-04			2.90E-04
Hydrogen Sulfide				1.30E+00	
Lead	3.06E-03	3.32E-03			5.41E-03
Nitric Acid	7.99E-04	6.20E-03	1.29E-03		5.28E-04
Sodium Hydroxide	4.01E-02	1.62E-02	2.67E-03	2.03E-03	2.65E-02
Sulfuric Acid		1.54E-03	6.41E-04	6.08E-04	

Fig. 2 Injury rate comparison of PV Technologies, including the contribution of each hazardous substance to the total risk indicator

The injury rate estimates illustrate a similar comparative relationship between the technologies as shown in Fig. 1 where CIGS is above c-Si estimates and CdTe are below c-Si estimates.

For CdTe, sodium hydroxide contributes most to the injury rate in contrast to the fatality rate since it is a corrosive substance, which could cause more probable injuries rather than fatal events with respect to nitric acid that is also toxic. On the other hand, hydrogen sulfide contributes most to the injury rate for CIGS similar to the fatality rate. For mono-Si and multi-Si, the hazardous substances contributing most to the injury rate are hydrochloric acid, hydrofluoric acid, and sodium hydroxide. Finally, the tandem perovskite/Si injury rate performs better than the other PV technologies except for CdTe. In the case of tandem perovskite/Si, hydrochloric acid and sodium hydroxide contribute most to the injury rate.

6. Conclusions

This study presents a first step for the assessment of accident risk considering a full-chain perspective of the most important PV technologies, including mono-Si, multi-Si, CdTe, CIGS, and tandem perovskite/Si, to be added in a comparative assessment for energy technologies (Spada, Sutra, and Burgherr 2021). In particular, it focused on the comparative accident risk assessment for PV manufacturing, which is quantitively assessed using the accident risk of hazardous substances involved in panel production.

Two research questions concerning the PV manufacturing accident risk were addressed. First, “What are the most hazardous substances in the PV manufacturing?”. Based on the results, hydrochloric acid, hydrofluoric acid, and sodium hydroxide are the most significant hazardous substances based on their contribution to the estimated fatality and injury rates and high use in panel production. Hydrogen sulfide is the most significant hazardous substance for CIGS.

Second, “Which PV technologies pose a higher risk in the manufacturing context?”. Based on the results, the risk contribution of hydrogen sulfide indicates that CIGS has the worst risk performance in comparison to the other technologies, while CdTe performs best due to the limited use of hazardous substances in production. Mono-Si performed comparatively better than multi-Si due to its higher conversion efficiency and the lower use of hydrofluoric acid in production. Finally, tandem perovskite/Si performed better than the other PV technologies, except for CdTe, due to its higher assumed conversion efficiency and reduced use of hydrofluoric acid in final panel production.

Future improvements will focus on a better estimation of the risk indicators based on the regional share of PV manufacturing and importing/exporting of the hazardous substances. Furthermore, in the context of a full-chain approach of energy technologies, accident risk related to operational and installation phases beyond manufacturing should be included. Finally, accident risk indicators for the PV energy chain should be put in a holistic context for comparative accident risk assessment with other energy technologies similar to Burgherr and Hirschberg (2014).

The latter is essential to support stakeholders in complex decision-making processes to plan, design and establish supply chains that are economic, efficient, reliable, safe, secure, and sustainable.

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