EVALUATION OF RISKS IN THE LIFE CYCLE OF PHOTOVOLTAICS IN A COMPARATIVE CONTEXT

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ABSTRACT: The greatest potential risks in the photovoltaic (PV) fuel cycle probably are associated with using some hazardous substances during cell material production and module manufacturing. To investigate the characteristics of these risks, we first identified the types and amounts of hazardous substances used during the life cycle of PV systems. Then, we estimated the normalized risks, i.e., accidents, fatalities, and injuries per gigawatt-year of electricity produced, along with the maximum consequences during the PV fuel cycle, based on the U.S. EPA Risk Management Program database of chemical accidents involving listed hazardous substances that are also used in solar cell or PV module manufacturing (e.g., AsH_3, PH_3, $SiHCl_3$, H_2Se, HF, HCl, SiH_4). Since incident data for the PV industry were not available, the evaluation of PV risks had to rely on the information from the chemical industry. Our analysis shows that, in terms of statistically expected incidents in the U.S., the PV fuel cycle is much safer than conventional sources of energy (e.g., coal, oil, gas, nuclear, hydro), and by far the safest in terms of potential maximum consequences. A framework is proposed by Brookhaven National Laboratory that encompasses a holistic view of risks and benefits and could allow more comprehensive comparisons; work is in progress to integrate this framework with the ERMON information system being developed by the Institute for Energy of the European Commission's Joint Research Center.
Keywords: Photovoltaic, Life Cycle, Risk

1. INTRODUCTION

Recent progress in the production capacity of the solar electric sector, along with its excellent environmental profile, highlights the potential of this technology to supply society with a large, sustainable source of electricity. Photovoltaic (PV) modules produce, throughout their lifetime, only a small amount of greenhouse-gas (GHG) emissions, i.e., 21-45 g CO_2-eq./kWh and have Energy Payback Times of 1 to 2.5 years [1,2] in average U.S. solar conditions. Furthermore, the life-cycle occupational risks of the PV fuel cycle, updated for modern PV plants, are relatively low [3]. However, little is known about the risks of accidental events, i.e., their frequency and scale that entail human fatalities, injuries, and economic losses in the PV fuel cycle. As discussed in previous studies, perhaps the greatest potential risks of the PV fuel cycle are associated with chemical usage during the stages of materials production and module processing [4,5]. We first identified a framework for assessing risks during the PV fuel cycle, and then examined and quantified those from chemical accidents, based on the U.S. EPA's Risk Management Plan (RMP) database. This database includes all incidents that harmed, or had the potential to harm, workers and/or the public. The risk indicators we investigated include the frequency of events, fatalities, injuries, and their maximum consequences. These indicators were normalized by the amount of chemicals used during the PV fuel cycle, both as feedstock and as consumables, including materials used upstream in materials processing. Finally, we compared our findings with the risks of severe accidents in other major energy sectors, such as coal, natural gas, oil, and nuclear energy.

2. CLASSIFICATION OF RISKS

Electricity is an indispensable element of social well-being and economic development in modern society. But, the costs that balance such benefits often are incompletely accounted for, and many potential harmful consequences to humans and ecological health are not fully addressed. Figure 1 presents a framework explaining this concept. The goal of our analysis was to assess and compare the risks associated with the PV fuel cycle with those of other electricity-generation technologies. Our focus is on the risks of accidental routine/severe incidents.

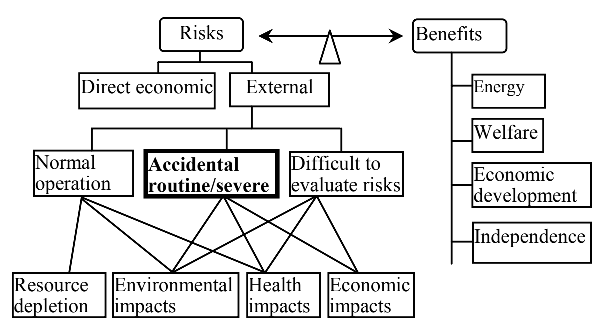

Figure 1: Framework for Evaluation of Life-Cycle Risks in Electricity Production.

We also developed a framework to sort the risks associated with energy technologies in four categories. The first category of risks is triggered by stressors at one or more stages of the fuel cycle for each technology; these events are common in normal operation and are not considered accidents. Their impact is usually limited by

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the enforcement of safety procedures during normal production. For most energy technologies, they are often overlapped with sustainability indicators determined by analytical tools, such as life cycle analysis (LCA) and impact pathway analysis. The second and third categories analyze infrequent and or anomalous events that should not occur during normal operation. Their scale and characteristics vary across energy technologies. Severe and catastrophic accidents with a very low probability of occurrence often are assessed and managed in a different way than small-scale accidents. Modern decision analysts are not interested in expected risk; instead, they focus on expected maximum risk [6] because the general public is more concerned about low-probability catastrophic events than high-probability less severe accidents. Calamities, such as dam bursting, airplanes crashing, and nuclear-reactor meltdown, are good examples of the latter. The fourth category encompasses events that may be triggered during a specific fuel-cycle stage but whose consequences are not amenable to qualitative- or quantitative-evaluation. Such events often are associated with the perception of risk in a population and may have great or negligible impact, depending on a variety of factors that standard risk-analysis procedures may not be able to account comprehensively.

Table 1: Risk Classification

	Definition	Impacts
Normal Operation	Typically accepted consequence s	- GHG emissions - Toxic chemical emissions - Radioactive emissions - Chemical/radioactive waste - Resource (fuel, water) depletion
Accidental Routine	High frequency / Low consequence s	- Leakage of chemicals – Health & environmental - Explosion/fires - Transportation accidents - Radioactivity release
Accidental Severe	Low frequency / High consequence s	- Core meltdown - Collapse of dam - Fire/explosion
Difficult-to-evaluate-risks	Risks subject to, and sometimes reinforced by perception	- Terrorist attack on reactor/used fuel storage - Geopolitical instability, military conflicts - Energy security/National independence - Nuclear proliferation

3. RISKS OF ACCIDENTS IN THE PV LIFE-CYCLE

The scope of the current analysis encompasses the life-cycle stages of PV energy: acquiring raw materials; producing materials; manufacturing modules; installing modules; generating electricity; and, disposing /recycling modules and equipment (Figure 2). The greatest potential hazard is often considered the release of toxic or flammable chemicals while producing cell modules; other fuel cycles pose risks of a different nature and type to employees and the public. Our data gathering and analysis for this study centered on incidents that involved handling and using the chemicals used for making solar-cell materials and manufacturing the modules. The risks of potential accidents in other stages of the life cycle are minimal and are not quantified in this analysis.

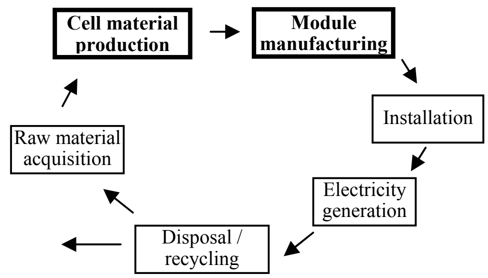

Figure 2: The stages of the photovoltaic fuel cycle.

4. RISKS OF CHEMICALS IN PV FUEL CYCLE

The Clean Air Act Amendments of 1990 requires the US Environmental Protection Agency (EPA) to regulate and guide facilities that use extremely hazardous substances to prevent chemical accidents. The US EPA's Risk Management Program's (RMP's) Rule in accordance with Section 112(r) of the amendments prescribes the regulatory requirements for facilities that handle certain toxic (77) or flammable (63) chemicals, in quantities larger than chemical-specific thresholds. Under this rule, such facilities have to submit a Risk Management Program (RMP) that includes a hazard assessment based on the most likely and the worst release scenarios. The program must be resubmitted every 5 years and revised whenever there is a significant change in usage. Part of the RMP submission is the five-year accident history for the facility [7]. In 1999, around 15,000 facilities filed RMPs that contained the history of accidents between mid-1994 and mid-1999; the current, updated RMPs mostly cover the accidents that occurred since mid-1999 for 17,000 facilities in the United States. Table 2 lists the chemicals used in PV industries under the RMP rule requiring a hazard assessment and accident reporting.

Table 2: Substances used in PV module manufacturing that regulated under RMP

Substance	Source	Quantity (25 MW/yr)
TOXIC		
Arsine	GaAs CVD	-
Boron Trichloride	Dopant	-
Hydrogen Sulfide	CIS sputtering	-
Phosphine	a-Si dopant	1.44 kg (a-Si)
FLAMMABLE		
Dichlorosilane	a-Si and x-Si deposition	-
Hydrogen	a-Si deposition/GaAs	-
Trichlorosilane	Precursor c-Si	3400 MT(c-Si)

Hydrogen Selenide	CIGS selenization	-
Hydrogen Fluoride	Etchant	20 MT (c-Si)
Silane	a-Si deposition	4 MT (a-Si)
Hydrochloric acid	Cleaning agent	16 MT (c-Si)
Boron Trifluoride	Dopant	-
Diborane	a-Si dopant	0.81 kg (a-Si)

MT=metric ton, CVD=chemical vapor deposition, CIS=$CuInSe_2$, CIGS=$Cu(InGa)Se_2$

We analyzed the EPA's current and past RMPs to estimate normalized accidents, fatalities, and injuries associated with the PV fuel cycle. The RMP reports cover accidents during the production, storage, and delivery of flammable or toxic chemicals. Table 3 shows the recorded number of accidents/death/injuries along with annual consumption figures in the United States from 1994 to 2004 for substances that are present in PV-module production. Since there are very few data on the production/consumption of trichlorosilane ($SiHCl_3$), those amounts are estimated based on polysilicon production and capacity data. About 2 kg of polysilicon are needed to produce a module of 6 x 12 cells of 125 mm x 125 mm, and 11.3 kg of trichlorosilane input is required to produce 1 kg of polysilicon [8,9]. No accidents were reported in the RMP database for phosphine and diborane during the same period.

Table 3: Annual consumption and incident records for substances regulated under RMP

Substance	Total average U.S. production (1000 MT/yr)	Incidents (both employees and public) in the RMP database (1994-2004)		
		Incidents (#)	Injuries (#)	Deaths (#)
TOXIC				
Arsine	23[a]	2	1	0
Boron trichloride	NA	0	0	0
Boron trifluoride	NA	1	1	0
Diborane	~50[b]	0	0	0
Hydrochloric acid	3500[c]	28	12	1
Hydrogen fluoride	190[d]	165 (57)*	209 (70)*	1
Hydrogen selenide	N/A	4	17	0
Hydrogen sulfide	>110[e]	40	47	1
Phosphine	N/A	0	0	0
FLAMMA-BLE				
Dichlorosi-lane	N/A	2	0	0
Hydrogen	18000[c] m^3	57	65	4
Silane	8[f]	5	2	0
Trichlorosi-lane	110[g]	14	14	2

Sources: [a] [12]; [b] [13]; [c] [14]; [d] [10]; [e] [15]; [f] [16]; [g] [8].

*Number excluding incidents in petroleum refineries (NAICS 32411)

We note that the number of occurrences shown in Table 3 represents the total for all the U.S. facilities that produce, process, handle, and store these chemicals. These statistics may or may not include facilities manufacturing PV modules. The majority (61%) of accidents/death/injuries attributed to hydrogen fluoride (HF) occurred in petroleum refineries (NAICS 32411), although such refinery use accounts for only 6% of the U.S. consumption [10]. The petrochemical industry uses 100% HF under high pressure in large, multi-component units (e.g., alkylation units with many pipes, fittings, valves, compressors, and pumps) from where two-phase releases may occur, whereas the use of HF in the PV industry is limited to aqueous solutions (typically 49%wt) in etching baths. Moreover, the usage of HF and hydrogen chloride (HCl) in the U.S. PV industry accounts for less than 0.1% of the total in the United States. Therefore, we excluded HF use in the petroleum industries and the corresponding accidents from the analysis for determining risks in the PV fuel cycle.

Table 4 breaks down the types of accidents for trichlorosilane and silane. Liquid spill/evaporation was the main cause of events involving trichlorosilane, while gas release was more a frequent cause of accidents with silane. The latter is more likely to cause a fire than the former. There exist many release points; piping is the commonest source of release for trichlorosilane, but no information is given in the RMP database on the source of silane releases.

Table 4: Frequency of type and source of release

	Incidents	Trichlorosilane	Silane
Type of release	Gas release	4	4
	Liquid spill /evaporation	12	1
	Fire	3	3
Source of release	Storage vessel	0	2
	Piping	11	2
	Process vessel	3	1
	Transfer hose	4	0
	Valve	1	1
	Joint	1	0
	Pump	1	1

Notes: Total number of incidents: Trichlorosilane =14, Silane=5. Some incidents have multiple types and sources of release.

To normalize the rate of accident/death/injuries, the figures are divided by the amount produced for those chemicals in the United States. The risks of each substance used in a 25 MW/yr scale PV industry are determined based on the amount of materials in Table 2. Then, the number of accidents/death/injuries per GWyr of electricity produced is determined as a risk indicator of chemical accidents in the PV fuel cycle based on the average U.S. insolation of 1800 $kWh/m^2/yr$ and a performance ratio of 0.8 (i.e. 20% system loss).

Figure 3 presents the rates of accidents/death/injuries for c-Si per GWyr electricity produced based on the average U.S. insolation, 1800 $kWh/m^2/yr$. We focused on the most recent incident data (i.e., data submitted from 1999 onwards) that better represent the current evolution of the fast-growing PV industry. In general, for most chemicals, the numbers of accidents reported for the second cycle in the RMP (second half of 1999 to 2004) are lower than those reported in the first cycle (1994 to the first half of 1999). Specifically, only one accident involving silane was reported during the second cycle of the RMP, whereas four accidents occurred reported during the first cycle. Likewise, the number of accidents during the second RMP cycle involving trichlorosilane was reduced from 13 to 1 between the periods of 1994-1999 and 1999-2004. The reduction of incidents across the board, likely represents improved safety records in the whole U.S. industry.

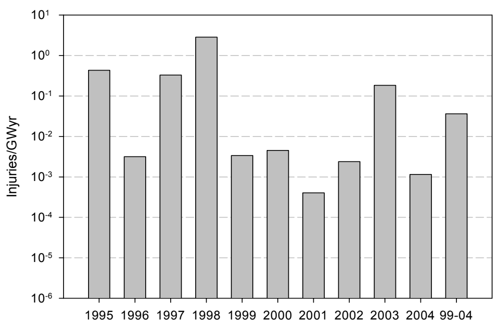

Figure 3: Estimated injury rates of c-Si per GWyr electricity produced in the US based on the year of accidents for HF, HCl and $SiHCl_3$. (insolation = 1800 kWh/m^2/yr, performance ratio = 0.8)

For c-Si PV modules, $SiHCl_3$, the feedstock of polysilicon presents greater risks than other chemicals (Figure 4). On the other hand, it appears based on limited statistics, that silane poses the greatest risk in a-Si module manufacturing. The fatalities in Figure 4 are related to HF. However, this risk is not based on the real event in PV facilities but is virtual risk that is derived from accident rates in other industries and the amount consumed in the PV industry. The real risk of HF in the PV industry however, is likely to be lower than the current estimation in Figure 4, as discussed above due to the different characteristics of processes across industry sectors.

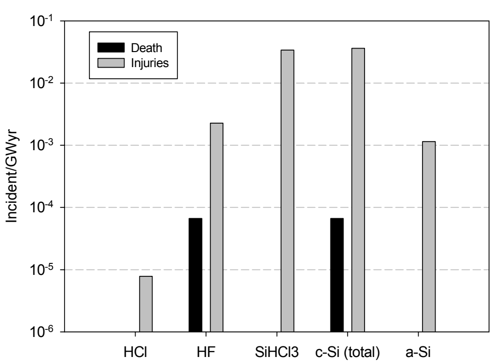

Figure 4: Estimated incident rates by chemicals used between 1999-2004 (insolation = 1800 kWh/m^2/yr, performance ratio = 0.8). The incident rate of a-Si covers 1997-2004.

5. COMPARISON WITH OTHER ENERGY TECHNOLOGIES

Figure 5 compares fatality and injury rates across conventional electricity technologies and PV technologies. The figures for the conventional fuel cycles were extracted from the compilation of severe accident records of the GaBE project by the Paul Scherrer Institute (PSI), Energy-related Severe Accident Database (ENSAD) from 1969-2000 [11]. Although such a direct comparison may not be entirely appropriate, Figure 5 suggests that the PV fuel cycle is better than other technologies in terms of expected risks.

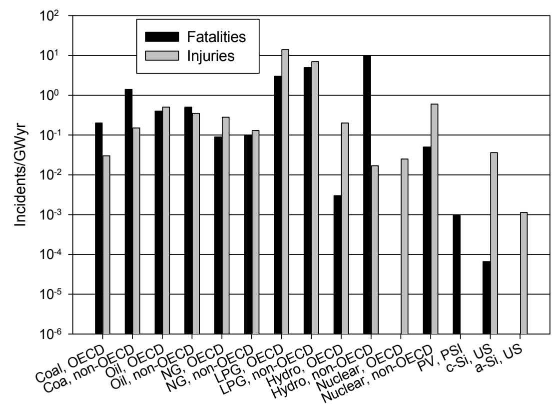

Figure 5: Comparison of fatality and injury rates across electricity-generation technologies. The average U.S. insolation = 1800 kWh/m^2/yr and a performance ratio = 0.8 was assumed. The incident rates for coal, oil, NG, LPG, hydro-, nuclear-, and PV technologies by PSI are from Hirschberg et al (2004) [11]. (NG=Natural Gas, LPG=Liquefied Petroleum Gas).

There are several caveats that must be addressed in directly comparing our estimate of PV risks and the risks estimated by the PSI investigators. First, the estimates by Hirschberg et al (2004) are based on severe accidents only, and ignore small-scale accidents; the former are defined as events with at least 5 fatalities, 10 injuries, $5 million of property damage, or 200 evacuees. On the other hand, only 20 out of the 318 occurrences shown in Table 3, can be classified as severe accidents. Therefore, the PSI's values for risk of conventional energy technologies may be underestimated. Also, we expect the evolving PV industry to keep improving their safety records with time, whereas the risk figures for the mature conventional energy technologies are likely to changes less. Furthermore, our analysis of PV risks represents the status of the industry in the United States, while the PSI analysis represents the Organization for Economic Co-operation and Development's (OECD's) and non-OECD's averages.

We also examined the maximum consequences of each energy technology. People are rarely neutral about risk; decision makers and risk analysts and the public are more interested in unforeseen catastrophes, such as bridges falling, dam bursting, and nuclear reactors exploding than in adverse, but routine events such as transportation accidents. Comparing low-probability/ high-damage risks with high-probability/low-damage events within one expected value frame often distorts the relative importance of consequences across technology options. Therefore, describing the maximum consequence potential makes sense [6]. Figure 6 shows the maximum fatalities recorded in accident databases. From a scale of consequence perspective, PV technology is remarkably safer than other technologies. It is expected that the maximum consequence will remain at the same level shown in Figure 6 unless a significant change occurs in PV production technologies.

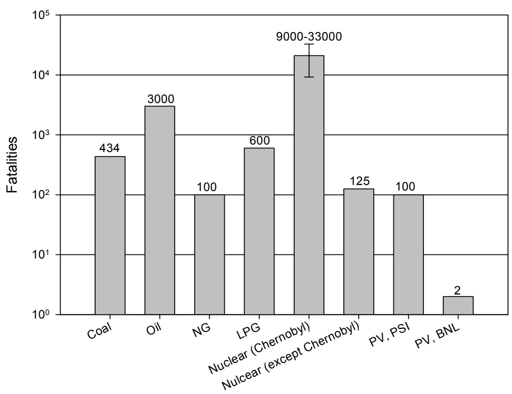

Figure 6: Maximum fatalities from accidents across energy sectors. The number for Chernobyl includes latent fatalities. The incident rates for coal, oil, NG, LPG, hydro, nuclear, and PV by PSI are from Hirschberg et al (1998) [5]. (NG=Natural Gas, LPG=Liquefied Petroleum Gas).

The nature of risks varies with different energy technologies. The PSI analysis focuses on fuel mining, fuel conversion, power-plant operation, and transportation of fuels. On the other hand, fuel-related or power-plant-related risks are non-existent in the PV fuel cycle. Instead, our analysis of PV risks focuses on accidents associated with feedstock materials as well as process consumables, i.e., upstream risks, which the PSI analysis does not include.

As we discussed, the hazards of trichlorosilane when making modules of c-Si, and of silane for a-Si modules have dominated concerns over other chemicals in the PV industry due to the large amount required and their flammability (Table 2). The limited number of incident records for them in the RMP database prevented us from accurately measuring the safety of the PV industry. Therefore, we undertook a sensitivity analysis by adding the incremental number of incidents to the figures between 1999-2004 involving trichlorosilane for c-Si, and silane for a-Si fuel cycle (Figure 7). Since death records are very rare for these chemicals (Table 3), the risk of fatalities is highly sensitive to a single incident. On the other hand, injury rates are relatively stable against the incremental number of injuries. This again illustrates that the scale of the PV industry in terms of capacity and employees still is small so that such analyses are inadequate for direct comparison with other technologies. PV technology is in the early stage of commercial application compared with other technologies, and risk-management programs complied through experience eventually should stabilize the number of abnormal incidents over time. Other technologies, such as nuclear power, experienced a similar period during the early years of commercialization.

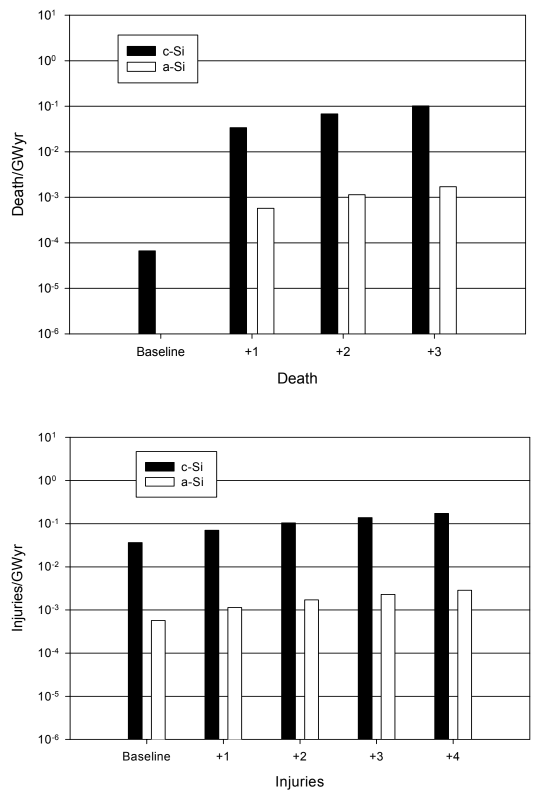

Figure 7: Sensitivity of risks against the number of death and injuries.

6. PROBLEMS IN RISK COMPARISON

The PV technology is at an early stage compared with other energy systems, but it is rapidly growing in a context of policy push at EU level to increase the contribution of renewable energies to the total EU energy mix [17, 18], there are strong efforts to boost the PV sector, and it should be treated more and more as an energy sector, avoiding the comparison with the chemical or semiconductor industry. The analysis conducted for risk in PV shows that this life cycle presents a level of risk lower than many other technologies. Given the situation, the PV industry should help in sharing information, which could surely give PV more credibility and transparency while helping in comparing risks.

When comparing risks in the wide context of different energy systems, the problem of the variety of the risk expressions is also encountered. Risk expressions resulting from different risk assessments can have a different form and often contain very different richness (not only quality) of information, and are thus often difficult or impossible to compare. This has significantly hampered the use of risk assessment for comparative purposes.

In risk assessment studies, both consequences and probabilities of an event may be expressed qualitatively or quantitatively, as well as in a more direct or a more indirect way, with a characterization that depends on the purpose/scope/methodologies of the risk study and can be more qualitative or more quantitative, more direct or more indirect.

Moreover, risk assessments have over the years have adopted their own scientific/technical terminologies and formats of presentation, leading to significant communication problems. Risk expressions are often not easily understood by stakeholders (policy, industry, public), the potential consequences of a particular hazard are often misunderstood and consequently hazards either significantly over- or under-estimated in the perception. The same is true for the difficulty of understanding probability [19].

Thus, a fair comparison methodology is needed in the energy sector to help interested stakeholders in making decisions.

7. COMPARISON USING INDICATORS

The EC-JRC's ERMON (Energy Risk Monitor) tool aims at allowing fair comparisons based on the concepts of Risk Characterization and Risk Qualification.

The development of both the risk characterization and risk qualification template of indicators to create an energy risk compass supported by the creation of an energy risk knowledge base, has the purpose to improve the understanding and the communication of risks among all stakeholders (policy-makers, public, utilities, etc.), and to increase the acceptance and use of risk assessment approaches.

The comparison focuses on two different aspects:

1. The first one is related to the physical extent and perceived relevance of the possible risk of a particular hazard.
2. The second one is related to the quality and richness of the information used in the assessments (data, assumptions, models, scenarios, etc.).

When put in an integrated form, both of them provide the user with the essential information necessary to judge the risk associated with different energy systems on the basis of the available information from published risk assessments or incident / accident statistics.

Such an energy risk knowledge base and tool present the benefit of providing users with a flexible methodology applicable to different energy systems in their fuel and life cycles. Furthermore, it allows different stakeholders to access and use the information according to their needs. Lastly, it provides a significant amount of valid information, which can lead to a comprehensive evaluation of a specific energy-related hazard. This will also provide information about the quality-related elements of the energy risk assessment underlying the considered risk expression, in order to allow a comparison of different understandings of similar hazards and different risks from different energy systems, in order to judge their sustainability and to make decisions concerning policy-related issues.

The first stages of the development of ERMON has led to the investigation of different available risk expressions (from risk assessments, reports, data, etc.), and of the steps along the energy chains into analysis (twelve chains considered - coal, natural gas, petroleum, nuclear, biomass, geothermal, hydro, solar, PV modules (life cycle), wind, wind turbines (life cycle), hydrogen).

This resulted into the development of a general scheme for all fuel/life cycles [20]. The scheme is characterized by four main steps: 1- production (related to all production operations); 2 - transportation (all transportation steps including raw material, waste, and storage); 3 - power generation (power plant, including construction and dismantling operations); 4 - waste treatment.

The general scheme allows the use of risk indicators describing different energy systems (see Figure 8); its completeness will vary according to the quantity of information and the characteristics of the energy chain into consideration.

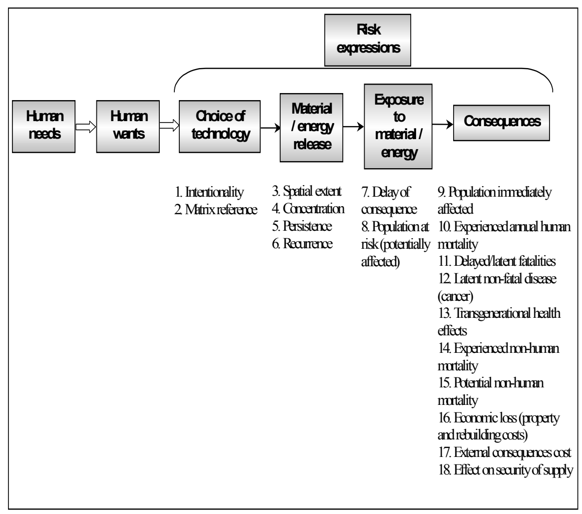

Figure 8: The ERMON risk indicators.

The aim of using risk indicators is to provide comparable information for managing risks. The basic model is the set of twelve numerically quantified descriptors developed by C. Hohenemser, R.W. Kates and P.Slovic [22] for technological hazards, a sequence of causally connected events leading from human needs and wants, to the choice of the technology and to the consequences caused by the release and the exposure to energy and/or material.

8. CONCLUSION

The photovoltaic manufacturing cycle entails the use of several hazardous substances, although in quantities much smaller than in the process industries. The greatest potential risks of the PV fuel cycle are linked with the accidental release of gaseous materials; however, the risks have not been well quantified in comparison with other electricity-generation technologies. We used the U.S. EPA's RMP accident records that cover the entire major US chemical storage and processing facilities to measure the risks associated with the PV fuel cycle. Our analysis shows that, based on the most recent records, the PV fuel cycle is much safer than conventional sources of energy in terms of statistically expected, and by far the safest in terms of maximum consequences.

Nevertheless, specific to the PV sector incident statistics which will allow well-balanced comparisons with other energy technologies are not available. Building a comprehensive framework for the comparison of energy generation options, based on the principles of life analysis and risk analysis, is of great interest in the European Union as well as the United States, to inform and assist decision making.

The ERMON tool proposed by the EC's JRC has the potential to allowing fair and qualified comparisons of energy technologies. Work is in progress in applying this framework to PV and other energy systems

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