A Methodology to Allow Comparison among Different Energy Systems

Proefschrift

May 2009

Alessandra Colli

A Methodology to Allow Comparison among Different Energy Systems

A.Colli

ISBN 978-90-5638-213-1

TU Delft Delft University of Technology

Challenge the future

Faculty of Technology, Policy and Management

A Methodology to Allow Comparison among Different Energy Systems

Proefschrift

ter verkrijging van de graad van doctor
aan de Technische Universiteit Delft,
op gezag van de Rector Magnificus prof. dr. ir. J.T. Fokkema,
voorzitter van het College voor Promoties,
in het openbaar te verdedigen
op woensdag 6 mei 2009 om 12:30 uur

door:
Alessandra COLLI
dottore in ingegneria elettrica
Politecnico di Milano, Italie
geboren te Verona, Italie

Dit proefschrift is goedgekeurd door de promotor:
Prof. dr. B.J.M. Ale

Samenstelling promotiecommissie:

Rector Magnificus, voorzitter	
Prof. dr. B.J.M. Ale	Technische Universiteit Delft
Prof. dr. J. Augutis	Vytautas Magnus University
Prof. dr. T. Aven	University of Stavanger
Prof. dr. H.J. Pasman	Technische Universiteit Delft
Prof. dr. N.D. van Egmond	Universiteit Utrecht
Dr. D. Serbanescu	European Commission, supervisor
Dr. K. Simola	VTT Technical Research Centre of Finland

The research described in this thesis has been supported by the Institute of Energy of the Joint Research Centre (JRC) of the European Commission, Westerduinweg 3, 1755 LE, Petten, The Netherlands.

ISBN 978-90-5638-213-1

PRINTED IN THE NETHERLANDS

PREFACE

In 2003, when the proposal to start a Ph.D. study on this subject was offered to me, I didn't really know what to expect. It was not connected to my previous background, if not for the only fact that it is dealing with energy systems and electricity production.
It was a challenge, but I met a different world, that thought me to look at energy production from a different perspective. Words like risk, hazard, probability, safety and security started to make sense to me.
The initial project was far more ambitious, aiming at becoming a standard in energy risk comparison. It was initially thought to become a web-based risk-information tool with the name of Energy Risk Monitor (ERMON). Traces of it and of the network that was created to support it can be found in the first paper included at the end of this thesis.
Later changes in management and work orientation, supported by various internal reorganizations in the institute where the work has been carried out, drastically imposed a change when the work was more or less in the middle of its way. The practical development of ERMON was definitely affected, at least for the time being.
But not everything bad happening to us is meant to hurt. Actually, that change of direction came out to be probably the best change I could ever expect! I came in contact with the world of probabilistic risk assessment (PSA) which offered me the input to solve one of the major problems encountered along the study: the grouping of the indicators and the ranking of the risks associated to events under investigation. Moreover, the accomplishment of the first PSA study for the photovoltaic manufacture industry could have been possible.
But this is not all, as it seems that PSA will probably accompany me also in the future, leading to the realization of one of my dreams since I started the university: to work in the field of nuclear.
With this occasion, I really want to thank from my heart the two most important persons along all the Ph.D. period: first of all my main coordinator from TU Delft, Prof. Ben Ale, for having accepted me as one of his Ph.D. students and for his constant support during the study; secondly, but not least, Dr. Dan Serbanescu, for having shared his knowledge (and the office) with me day by day in the last two years, and having believed in this work.
These are just few words to thank them, but what I keep in my heart is much more, and those two great persons will remain in my memory for the rest of my life.

Alessandra Colli
Bergen NH, March 2009

Content list

PART I

Introduction

1. Introductive overview.

1.1. Overview.

The use of different systems for the generation, transmission and distribution of energy is at the base of any advanced society. They provide the basic resources for industrial production, transport and domestic needs. Thus, energy resources in terms of available fuels and reliable infrastructure are needed. On the other hand, they involve hazardous activities that pose a threat to public health and environment. During the last years a lot of attention has been paid by regulators, utilities, environmental groups and the general public to risk issues related to the use of the different types of energy systems across the different steps in their fuel and life cycle chains.

At European level, the increasing intensity of external energy dependence (EU 27 energy dependence rate is 54% in 2006 (Eurostat, 2008)) – partly from regions threatened by insecurity (Green Paper, 2006) - together with the recent instability of oil prices [1], call for the implementation of renewable and alternative energy systems.

Europe is acting with an increasing involvement in energy issues. The European Community legislation in force concerning energy already consists of 350 acts (Directives, Regulations, Decisions, etc) (European Community Eur-Lex, 2008). A diversification of energy sources with the promotion of the development of new and sustainable energy technologies (e.g., Directive 2001/77/EC on the promotion of the electricity produced from renewable energy sources in the internal electricity market, and Directive 2004/8/EC on the promotion of cogeneration based on a useful heat demand in the internal energy market), is necessary to increase security and stability of energy supply to customers.

Anyhow, action is urgent: it takes many years to bring innovation on stream in the energy sector. Promotion of energy diversity – type, country of origin and transit – must be continuous. This approach will create the conditions for growth, jobs, greater security and a better environment. Work has been progressing on these issues since the Commission's 2000 Green Paper on Security of Energy Supply, but given recent developments on energy markets, a new European impetus is needed.

The European Green Paper on "A European Strategy for Sustainable, Competitive and Secure Energy" (Green Paper, 2006) identifies six key areas where action is necessary to address the challenges we face: (i) improvement in the internal energy market for growth and jobs, (ii) solidarity between Member States to guarantee security of supply, (iii) diversification of the energy mix, improving sustainability and efficiency, (iv) integrated approach to tackling climate change, (v) innovation through a strategic European energy technology plan and (vi) coherency in the external energy policy.

The issue of security of supply clearly includes tackling the EU's rising dependence on imported energy through an integrated approach – reducing demand, diversifying the EU's energy mix with greater use of competitive indigenous and renewable energy, and diversifying sources and routes of supply of imported energy, creating the framework which will stimulate adequate investments to meet growing energy demand, better equipping the EU to cope with emergencies, improving the conditions for European

companies seeking access to global resources, and making sure that all citizens and business have access to energy.
Improving use and diversification of energy sources and technologies means also understanding the different degree of threat they can pose to the community and the environment. And the scope of the risks comparison methodology is towards this direction, improving communication and understanding of risk issues for energy systems. In this context, the safety analysis of the various energy systems in a comparative view is important. In fact, talking about safety does not only mean to look at the safety assessment of the single energy chain, but also to consider a cross comparison among different energy technologies, at the level of the single step and/or of the complete chain of their fuel/life cycle, reaching a comprehensive energy risks comparisons.

1.2. State of the art.

The investigation of the international energy scenario shows that very few comparative risk assessments for energy systems are available, the main being the methodology offered by the Paul Scherrer Institut (see (Hirschberg et al., 1998) or more recently (Burgherr & Hirschberg, 2008)), while others are outdated in comparison to the present technological development (e.g. (Inhaber, 1980)).
Moreover, these studies are often not comprehensive of all energy systems and the related risk aspects. They offer unclear overall judgments, and are based mainly on historical events. But this is not enough if the aim is a reliable and complete comparison among all energy technologies.

1.3. The risk in the energy sector.

Energy systems have been developed to satisfy societal needs. The scheme in Figure 1.3.1 illustrates the interactions of energy technologies with the society and the all-embracing environment, allowing identifying the areas of interest for the energy risks comparative methodology under analysis. The three domains shown in the figure are working with continuous interconnections as communicating parts of the same entity.
The relations among the areas of energy technology, society, and environment focus on risks and sustainability issues.
Thus, for a complete and comprehensive analysis of all related aspects of an energy system with the surrounding world, issues like effects of risks on human health, property, and environment must be taken into consideration, as well as all concerns affecting the economical, environmental, social and institutional dimensions of sustainability.
Thus, risk and sustainability aspects meet in this general overview. Risk and sustainability are complementary concepts with different characteristics and contexts of application, the first mainly looking into consequences and probabilities, the second into benefits.
For example, risk is more focused on management strategies, which reflects the final intention to protect the status quo; it is also looking mainly into the negative outcomes affecting individuals and groups, and uncertainties are explicitly calculated. On the other side, sustainability is focused on development, aiming to evaluate the chosen system in its completeness, and uncertainty is only an implicit component.
"*Risk management and sustainable development are two strategic frameworks utilized for studying and managing the environmental consequences of human actions. As such, both*

frameworks require indicators with which to measure, monitor and communicate" (Gray, Wiedemann, 1999).

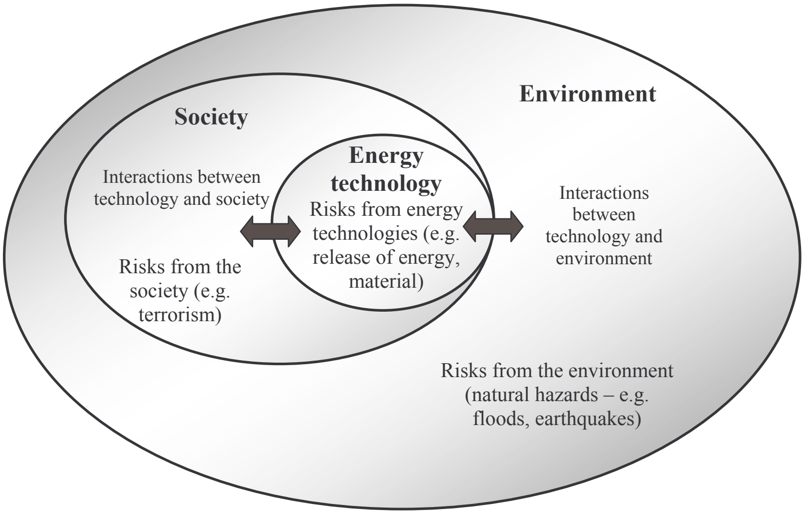


Figure 1.3.1: Interconnections and interactions of the energy technology area with the surrounding society and environment.

Considering the large amount of available sustainability studies developing indicators – see for example (IAEA et al., 2005) or (IAEA, IEA, 2001) or (OECD, 2004) – or studies looking into security of energy supply from a sustainability-oriented perspective (Scheepers et al., 2006), and taking then into account the lack of harmonization in risk communication due to a large variety of risk expressions interesting the energy sector, the intention of this project is to focus on risk aspects affecting the production of useful energy (mainly electricity). Being aware of the different points in common between the two parts of risk and sustainability, the door is left open for a possible future development of the sustainability aspects, to complete and enhance the presently developed methodology, providing the user of the tool with a wide and comprehensive view on energy issues to help decision making processes.

Before entering largely and deeply into the analysis of risk issues in the energy sector, it must be clarified what it is meant by an energy system and what by risk in the frame of this work.

An **energy system** is a complex process that transforms a primary energy source (substance or natural phenomenon) into useful power (that can be thermal, electrical, mechanical). Taking stock of various multi-dimensional aspects (human factors, technology, organization, policy, interactions with the environment, etc.), it is important to highlight the human factors aspect, because people are involved in the energy system both as executors of the fuel transformation and conversion, but also as end-users (Colli et al., 2008).

An energy system can operate using a single technology, or can use various technologies working in series and parallel for the purpose of producing useful energy.

Figure 1.3.2: Risk curve (Bedford & Cooke, 2001).

Although several definitions exist, in the context of this work **risk** is expressed in terms of consequences and probabilities associated to specific scenarios.
The original definition considered is from (Kaplan & Garrick, 1981), where it is stated that "*…a risk analysis consists of an answer to the following three questions:*

(i) What can happen? (i.e., What can go wrong?)
(ii) How likely is it that that will happen?
(iii) *If it does happen, what are the consequences?*"

This means that to identify a risk it is necessary to identify scenarios, probabilities, and consequences. Then, risk can be expressed as a set of triplets:
$R = \{(s_i, p_i, x_i)\}$, and $i = 1, 2, \ldots, N$.
If the scenarios are then arranged according to an increasing severity of damage, it is possible to draw a risk curve by plotting the points (x_i, P_i), where Pi identifies the cumulative probability. An example risk curve is shown in Figure 1.3.2 (Bedford & Cooke, 2001).
Taking this definition into account, **energy risks** involve accidental or voluntary events leading to unwanted consequences, with different probabilities, resulting by various possible scenarios, coming from normal operation or non-planned internal and/or external (to the involved technology) events resulting in human, economical, and environmental consequences. Energy risks are reported as **risk expressions** (Colli et al., 2008).

1.3.1. Framework of evaluation.

Energy, and especially electricity, is a fundamental contributor to 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 1.3.1.1 presents a framework explaining this concept and trying to evaluate the possible risks associated to electricity production (Fthenakis et al., 2006).

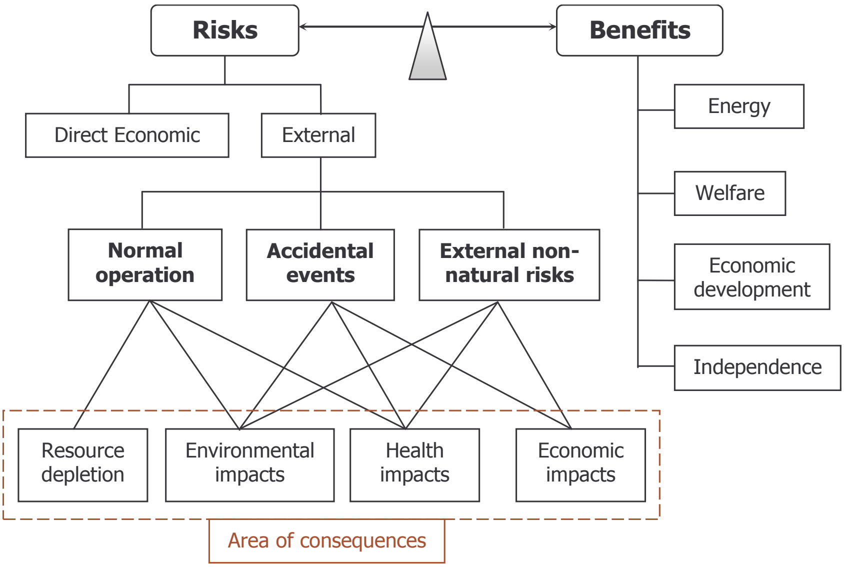


Figure 1.3.1.1: Framework for evaluation of fuel/life cycle risks in electricity production (Fthenakis et al., 2006). The larger development of the risk side is not associated with the dominance of risks in the energy sector, but it is only related to a deeper investigation to fulfil the scope of this study. Electricity production offers a wide range of benefits, from the energy availability for different purposes, leading to industrial and thus economic, development of the society, improving welfare, and societal independence from other countries, boosted by independence from external energy sources when possible. Anyhow electricity production has also a series of associated risks, mainly divided into direct economic and external, the first related to the energy market, and the second involving events external to the electricity itself as product.

The proposed framework, in its early risk-related stages, divides risk into two main categories, direct economic and external.
The direct economic risk is associated with the economical aspects of energy, related do the market infrastructure and development, financial support, etc, and is outside the scope of the present work, which wants to concentrate on the area of external risk. This part refers to risks coming from causes different from the primary energy production purpose of the energy systems. This side of the energy risks is divided into three major risk categories – normal operation, accidental events, and external non-natural risks – which will be discussed in detail in the following Section 1.3.2.
These three categories of risk could have different degrees of consequences affecting different areas as shown in Figure 1.3.1.1.
Economic, environmental, and health impacts are the areas of investigation having pertinence with this study.
Resource depletion is a sustainability issue and is not taken into consideration for the scope of this work. At the moment the comparison is based on the analysis of risk in terms of consequences and probabilities, according to the given risk definition (Section 1.3). As the method should become a tool based on data and information coming from different risk assessment studies, the analysis of the causes leading to a certain event are considered as

treated and evaluated into those risk assessments themselves, and thus out of the scope of the present investigation and methodology development.

1.3.2. Risk classification.

This section is extracted from (Colli et al., 2008), although some minor changes are introduced.

According to the plan shown in Figure 1.3.1.1, external risk concerning electricity production can be classified into three different categories:

1. Risks from normal operation.
2. Risks from accidental events (routine, severe, including risks from natural disasters).
3. Risks from external non-natural events.

The first risk category is triggered by elements at one or more stages of the fuel/life cycle for each technology; these events are common in normal operation and are not considered accidental. Their impact is usually limited by the enforcement of safety procedures during normal production (Fthenakis et al., 2006).

Ordinary toxic chemical emissions, as well as radioactivity releases due to normal operation activities can be listed under this category. Issues like greenhouse gases (GHG) emissions and resource depletion are clearly sustainability-related. It is acknowledged that the two concepts of risk and sustainability are complementary and both very important for managing energy related decisions (see also Gray, Wiedemann, 1999), but the focus of this work is only on risk-related aspects and in this context sustainability studies can be only referenced – e.g. indicators for GHG missions and available resources and reserves for critical fuels can be found in (IAEA et al., 2005).

A larger variety of events are then listed under the second category among accidental events, which have specific characteristics depending on the step of the chain and the affected energy technology, or are originated by natural disasters.

This second category analyzes 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, which are also less easily reported especially when the consequences are minimal.

This reflects the importance of taking into consideration “extreme” events as highlighted in (Haimes, 2004): “*For risk methodologies and tools to be useful and effective, they must be representative; that is, they must capture not only the average risks, but also the extreme and catastrophic ones*”. To be prepared to face expected unacceptable risks, modern decision analysts need to focus on expected maximum risk. Calamities, such as dams bursting, and nuclear-reactor meltdown, are good examples.

The third category covers events that may be originated during a specific fuel-cycle stage but whose consequences are not amenable to 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 (Fthenakis et al., 2006). This category wants to take into consideration issues related to geo-political instability, military conflicts or nuclear proliferation, which could be easily converted into the general problem of intentional terrorist actions and attacks to energy infrastructures with the intent to harm the population and cut the energy support in one or more countries. The case of terrorist attack against energy infrastructures is distinguished from events of the second category for the difference in the originating cause, not due to an intrinsic property of the system, but to the intentionality of the event.

The nuclear chain has to consider also the added risk related to nuclear proliferation, where nuclear knowledge, technologies, and materials can be used for the construction of nuclear weapons for war or terrorism purposes.

With a global view of the different types of energy-related risks, it is possible to describe events in terms of release of material (through atmospheric, liquid and solid pathways) and/or energy.

When treating the context of energy security, national energy independence is also relevant, but has been excluded from the scope of this study; its evaluation through the use of indicators is closer to sustainability and is left to that area of study – see, for example, the net energy import dependency indicator ECO 15 from (IAEA et al., 2005), or the case of supply/demand and crisis capability indicators from (Scheepers et al., 2006).

To give a valid support to the work, an investigation of the possible risk scenarios for different energy systems are evaluated and analyzed.

As shown also in Figure 1.3.1.1, the consequences will be evaluated for the three usual aspects of interest for risk:

1. Human.
2. Environmental.
3. Economical.

Moreover attention will be paid to time frame, and occupational and non-occupational aspects.

Considering the health impact, effects of energy technologies on humans can come from the following paths:

- Inhalation (e.g., toxic fumes, gases, etc.).
- Direct contact (e.g., materials, harmful substances, etc.).
- Thermal energy (e.g., fire).
- Mechanical energy (e.g., explosions, crashes).
- Radioactivity (e.g., radiological effects).

These different causes of risk for people lead to different degrees of consequences, which could result in immediate or delayed fatalities, injured, evacuees, or long-term health effects influencing also future generations (mainly related to radioactivity contamination).

The effects of energy technologies on the environment (estimated mainly using (Externe, 1997) and (Barbir at al., 1990)) can come mainly from the release of dangerous substances (with and without radiological effects) and thermal energy, producing consequences on:

- Live stock, with fatalities, injured, permanent damages, effects on future generations and on the animal natural habitat (animal are affected in a manner similar to human beings).
- Contamination of air, ground, water, and environmental goods with high concentration releases.
- Radiological impact level on animals and environment.

Resource and water depletion, global warming, and disturbance to the visual and acoustic amenity of neighbourhoods should be also mentioned as environmental effects, but more closed to sustainability issues and not considered in this study.

The economical effects of possible risks from energy systems can be separated into two categories: internal (direct economic consequences) and external (indirect economic consequences). The first one includes property and rebuilding costs or remedy for prevention/substitution. The second category is then separated into environmental (impact on public and occupational health, agriculture, forests, biodiversity effects, aquatic impact, impact on materials, global impact) and non-environmental (impact on public infrastructure, security of supply, government actions) effects (Hirschberg et al., 1998).

1.3.3. Risks in the energy sectors.

Once established the three category of energy risk which will be considered during the development of the RCIs – normal operation, accidental events, and external non-natural events – it is worth to investigate possible risk scenarios across the different types of energy technologies.

This investigation has been conducted grouping the various energy systems in groups of likeness, like fossil, nuclear and renewable technologies, while hydrogen, which is an energy carrier, represents a particular case and has been treated separately from the other energy systems. The results of the investigation are shown in Table 1.3.3.1.

The three categories of risk have been evaluated for four groups of energy technologies (fossil, nuclear, renewable energies, and hydrogen) across the four main steps of the general chain developed as a base for the methodology - production, transportation, power generation, and waste treatment (Colli et al., 2005-b). The possible risk scenarios are thus distinguished for different stages across the fuel/life cycles. It is important to note that the table has been filled in with the available information, which could have been found through reported accident data and safety studies, and wants to show representative examples of possible risks, but the list in the table does not claim to be fully complete and comprehensive.

Looking at Table 1.3.3.1 it is immediately clear that external non-natural risks present the same scenario for every energy system at all steps of the chain. This is due to the fact that the events are completely independent from the specific energy technology into consideration; they are not due to an intrinsic property of the system, but to completely external origins and causes. Only the nuclear chain has the added risk related to nuclear proliferation, where nuclear knowledge, technologies, and materials can be used for the construction of nuclear weapons for war or terrorism purposes.

Table 1.3.3.1: List of some possible risks for different energy sectors.

Stages of the general chain	**Risk classification**	**Possible risks from fossil technologies**	**Possible risks from nuclear technologies**	**Possible risks from renewable technologies**	**Possible risks from hydrogen technologies**
Production	*Normal operation*	Dust emissions, toxic emissions	Radioactive emissions, toxic emissions, waste production	Toxic emissions	Risks from the upstream chain

	Accidental events	Spill, leaks, explosions and fires in underground mines, collapse of roof or walls in underground or surface mines, off-shore rig accidents, fire or explosions from leaks or process plant failures, well blowouts causing leaks	Radioactivity release, release of toxic substances	Spill, leaks, well blowout (geothermal), release of toxic substances	Leaks, embrittlement, fires, deflagrations, detonations
	External non-natural risks	Terrorist actions and attacks	Terrorist actions and attacks, nuclear proliferation	Terrorist actions and attacks	Terrorist actions and attacks
Transportation	*Normal operation*	Toxic emissions	Toxic emissions	Toxic emissions	Toxic emissions
	Accidental events	Haulage/vehicular accidents, transportation accidents resulting in fires, explosions or major spills, loss of content in storage farms causing fire or explosions	Accidents during shipment of high level radioactive material or waste, radioactivity release	Haulage/vehicular accidents	Haulage/vehicular accidents, leaks, fires, deflagrations, detonations
	External non-natural risks	Terrorist actions and attacks	Terrorist actions and attacks	Terrorist actions and attacks	Terrorist actions and attacks
Power generation	*Normal operation*	Radioactive emissions (coal), toxic emissions	Radioactive emissions, toxic emissions	Toxic emissions	Toxic emissions (limited, e.g. NOx emissions (Rambach, Haberman, 1997))
	Accidental events	Fire, explosions, release of toxic substances	Fire, explosions, radioactivity release, loss of coolant water or reactivity transient and reactor meltdown	Fire, explosions, rupture or overtopping of dam, fall out of material (wind turbines), release of toxic substances	Leaks, embrittlement, fires, deflagrations, detonations
	External non-natural risks	Terrorist actions and attacks	Terrorist actions and attacks, nuclear proliferation	Terrorist actions and attacks	Terrorist actions and attacks
Waste treatment	*Normal operation*	Toxic emissions	Radioactive emissions, toxic emissions	Toxic emissions	Not identified

	Accidental events	Leaks, soil contamination	Leaks, soil contamination, radioactivity release	Leaks, soil contamination	Not identified
	External non-natural risks	Terrorist actions and attacks	Terrorist actions and attacks	Terrorist actions and attacks	Not identified

Normal operation activities have the main hazard represented by the emission of toxic substances, and, in particular cases including not only the nuclear technologies, also the release of limited amount of radioactivity has to be considered.
A larger variety of events is then listed among accidental events, which are more characterized by the step in the chain and the energy technology under consideration.
With a global view among the different types of risks listed in Table 1.3.3.1, it is possible to depict all events in terms of release of material (through atmospheric, liquid and solid pathways) and/or energy.

1.4. References.

(Barbir et al., 1990) – F. Barbir, T.N. Veziroglu, H.J. Plass Jr., “Environmental Damage Due to Fossil Fuels Use”, International Journal of Hydrogen Energy, Vol. 15, No. 10, pp. 739-749, Pergamon Press, 1990.

(Bedford & Cooke, 2001) – T. Bedford, R. Cooke, "Probabilistic Risk Analysis. Foundations and Methods", ISBN 0-521-77320-2, Cambridge University Press, 2001.

(Burgherr & Hirschberg, 2008) – P. Burgherr, S. Hirschberg, "Severe Accident Risks in Fossil Energy Chains: A Comparative Analysis", Energy, Volume 33, Issue 4, April 2008, Pages 538-553, http://dx.doi.org/10.1016/j.energy.2007.10.015

(Colli et al., 2008) - A. Colli, A.L. Vetere Arellano, C. Kirchsteiger, B.J.M. Ale, "Risk characterisation indicators for risk comparison in the energy sector", Safety Science, 47 (1), pp. 59-77, Elsevier, Jan 2009, http://dx.doi.org/10.1016/j.ssci.2008.01.005

(Colli et al., 2005) - A. Colli, A.L. Vetere Arellano, C. Kirchsteiger, “Development of a General Scheme for Fuel Cycles and Life Cycles from all Energy Technologies as a Basis for the European Energy Risk Monitor (ERMON)”, EUR 21735 EN, Publication of the European Commission Joint Research Centre, Petten, The Netherlands, 2005.

(de Wit, 2006) – J. De Wit, “Safety Matters. Experience with the Operation of Gas Engine CHP Units”, from the journal “Cogeneration and On-Site Power Production”, pp. 43-48, September-October 2006.

(Externe, 1997) – compiled by P. Mayerhofer, W. Krewitt, R. Friedrich, “Extension of the Accounting Framework”, EXTERNE Core Project, funded in part by the European Commission, with contribution from CEETA, CIEMAT, IEFE, IER, VTT, ZEW, December 1997.

(European Community Eur-Lex, 2008) - http://eur-lex.europa.eu/en/legis/20080701/chap12.htm

(Eurostat, 2008) –
http://epp.eurostat.ec.europa.eu/pls/portal/docs/PAGE/PGP_PRD_CAT_PREREL/PGE_CAT_PREREL_YEAR_2008/PGE_CAT_PREREL_YEAR_2008_MONTH_07/8-10072008-EN-AP.PDF

(Fthenakis et al., 2006) – V.M. Fthenakis, H.C. Kim, A. Colli, C. Kirchsteiger, “Evaluation of Risks in the Life Cycle of Photovoltaics in a Comparative Context”, 21st European Photovoltaic Solar Energy Conference and Exhibition, 4-8 September 2006, Dresden, Germany.

(Gray, Wiedemann, 1999) - P.C.R. Gray, P.M. Wiedemann, “Risk Management and Sustainable Development: Mutual Lessons from Approaches to the Use of Indicators”, Journal of Risk Research 2 (3), (1999), pp. 201-218.

(Green Paper, 2006) – Commission of the European Communities, "GREEN PAPER. A European Strategy for Sustainable, Competitive and Secure Energy", http://ec.europa.eu/energy/green-paper-energy/doc/2006_03_08_gp_document_en.pdf

(Haimes, 2004) – Y.Y. Haimes, “Risk Modeling, Assessment, and Management”, John Wiley & Sons Inc., second edition, 2004, ISBN 0-471-48048-7.

(Hirschberg et al., 1998) - S. Hirschberg, G. Spiekerman, R. Dones, "Project GaBE: Comprehensive Assessment of Energy Systems. Severe Accidents in the Energy Sector", First edition, Paul Scherrer Institut, ISSN-1019-0643, (1998).

(IAEA et al., 2005) - International Atomic Energy Agency, UN Department of Economic and Social Affairs, International Energy Agency, Eurostat and European Environment Agency “Energy Indicators for Sustainable Development: Guidelines and Methodologies”, IAEA, Vienna, (2005), http://www-pub.iaea.org/MTCD/publications/PDF/Pub1222_web.pdf

(IAEA, IEA, 2001) - IAEA, IEA, “Indicators for Sustainable Energy Development”, (2001), http://www.iea.org/textbase/papers/2001/csd-9.pdf

(Inhaber, 1980) – Inhaber, H., 1980, “Risk of Energy Production”, Atomic Energy Control Board Rep. AECB 1119/REV-3, 4th edition, Ottawa, Canada.

(Kaplan & Garrick, 1981) – S. Kaplan, B.J. Garrick, "On The Quantitative Definition of Risk", Risk Analysis, Vol. 1, No. 1, 11-27, 1981.

(OECD, 2004) – OECD Environment Directorate "OECD Key Environmental Indicatrs", Paris, France, 2004, http://www.oecd.org/dataoecd/32/20/31558547.pdf

(Rambach, Haberman, 1997) - G. Rambach, D. Haberman, "Renewable, Hydrogen-Based Energy For Isolated Communities Worldwide", http://www.hydrogenassociation.org/newsletter/ad22isol.htm

(Scheepers et al., 2006) – M. Scheepers, A. Seebregts, J. De Jong, H. Maters, “EU Standards for Energy Security of Supply”, Energy research Centre of the Netherlands (ECN) and Clingendael International Energy Programme (CIEP) publication, report number ECN-C-06-039/CIEP, June 2006.

[1] - http://www.oil-price.net/

2. Goals and method.

2.1. The reasons behind the work.

The possibility to compare risks associated to different energy systems is important in the decision making context. Anyhow, performing this kind of comparison can face two main problems.
The first problem is the large variety of available types of risk expressions. Risk expressions may be either numerical ("operating pipeline technology A has a probability of 10^{-3} for at least 1 fatality per year") or more qualitative ("operating pipeline technology A is 10 times more hazardous than operating pipeline technology B") and, within the numerical case, they may be based on actual historical data, such as frequencies of certain types of incidents/accidents ("over the last 20 years, operating pipeline technology A had an accident rate of 0.25 per year"), or on prognostic studies, such as maximum effect distances ("when operating pipeline technology A the recommended safety distance is 100 m as regards likely lethal human health effects") or maximum number of expected fatalities ("when operating pipeline technology A for 25 years, the expected number of fatalities is 0.1"). This fact makes performance of comparisons difficult for non-experts and results not easy to communicate. It must be also considered that the assessment background of these risk expressions can be very dissimilar, leading to large differences in the quality of the information available. The data underlying these estimates can originate from technology specific probabilistic studies, from specific historical operating experience or from transfer of operating experience from similar (generic) technology to the specific one of interest. Further, the risk expressions can be based on different types of models, quality assurance and peer review schemes etc. This needs to be evaluated. A quality evaluation in term of uncertainty is needed both for the energy risks comparative process itself and for the input data, whenever the uncertainty value is not available from the source of information.
The second problem is the unavailability of reliable risk expressions for new energy systems which just entered the energy market in recent years, or which are now approaching the market. Let's take for example the case of photovoltaic solar energy, a fast growing technology. This is a safe and emission free technology concerning electricity production, but various hazardous chemical substances are used in the production process of photovoltaic cells. Anyhow, risks are evaluated using life cycle analysis in this field, and often the semiconductor industry is taken as a benchmark, but no clear risk evaluations are offered for the photovoltaic industry and no historical accidental events are available. This makes the comparison with other energy systems difficult to be performed.

2.2. Aim of the thesis

Given the problems highlighted in the previous section, the aim of this thesis is to provide a possible solution, able to offer a clear, valid, and comprehensive risk comparison in the energy sector. Different aspects must be considered to address such a purpose.
First of all, action is required to uniform the terms of comparison. The concept of comparison assumes already the similarity of the objects to be compared: obviously, they

must be of the same kind, and the values must be expressed in the same reference unit. For this purpose, a set of indicators covering the fundamental aspects of risk is selected. This solution is contemplated for the possibility to be applicable to all energy systems in a way to make comparison easier, expressed by common units or designations, and thus comprehensible not only to experts.

To enhance the comparison, overall risk values are needed, which could identify the risk level of specific pieces of information. To obtain such a result, a valid approach must be identified, restricting the amount of subjectivity in the methodology as much as possible.

Anyhow, this approach assumes that existing risk expressions are available. But, where historical events are not registered and no reliable risk expressions are obtainable, then it is necessary to rely on prognostic studies. Here is where the use of probabilistic risk analysis (PSA) could help.

At this stage, it is clear that two parallel assessments are performed, the first to process historical risk information, and the second to evaluate new energy systems. They lead to values of incomparable nature, as they originate from different approaches. As the aim of the work is to allow a comprehensive risk comparison, a solution must be found to solve this incompatibility.

2.3. General overview of the methodology.

The methodology developed along this thesis is illustrated in the scheme of Figure 2.3.1; it follows two parallel paths, one for existing risk expressions, and the other for new energy systems. The first requires the development of a specific approach and represents the core of this thesis, while the second only wants to support the use of PSA techniques for new energy technologies to evaluate risk where no historical events are already registered.

The main stream of the development is based on the backbone of a causal structure for hazard development of energy technologies, where the attempt to uniform the various risk expressions is based on a set of risk characterisation indicators (RCIs).

The relevance of using indicators as a way to express risk comparison is discussed by Gray and Wiedemann in (Gray, Wiedemann, 1999).

"*Indicators are a basic tool of management in any sphere, in particular for describing and monitoring the situation being managed, to help assess the available management options, and to evaluate the outcomes of actions taken. In addition, indicators are important in the communication between various stakeholders, which is involved in all these functions. The basic, inherent difficulty with indicators is that they are selective. They each represent one measure of one aspect of any situation. This means that there is always room for discussion and even disagreement about whether they really represent that which one wants to measure; whether other people want to measure the same thing; and whether the measure is understandable to non-experts*".

The reported statement also highlights a basic difficulty when dealing with indicators: the problem of the clarity and exactness of the definitions. Indicators should be clearly defined and definitions play a fundamental role.

The choice of using indicators has been taken in view of a large audience, which the method wants to be addressed to. In this situation the need to pass through common units has been encountered, and the risks are ranked on a relative basis.

The RCIs have the purpose of characterising different aspects of risk. In (Stern, Fineberg, 1996) the proposed definition for risk characterization is: "*risk characterization is a* *synthesis and summary of information about a potentially hazardous situation that addresses the needs and interests of decision makers and of interested and affected parties. Risk characterization is a prelude to decision making and depends on an iterative analytic-deliberative process*". The RCIs 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.

For the development of a valid set of indicators, it is first necessary to investigate the ground on which the work is carried on. Thus the first stages of the development of the method lead to the investigation of:

- Different available risk expressions, from risk assessments, reports, data, etc.
- The main characteristics of different energy systems across the steps of their energy chains (total of ten chains considered - coal, natural gas, oil, nuclear, biomass, geothermal, hydro, solar, wind, and hydrogen).

The evaluation of the first topical area has led to the identification of the most risk-prone step(s) within the various energy fuel/life cycles, while the second one has resulted in the development of a general chain scheme for all fuel/life cycles (Colli et al., 2005-a). This scheme is characterised by four main steps:

- Production - related to all production operations.
- Transportation - all transportation steps, including raw material, waste, and storage.
- Power generation - power plant, including construction and dismantling operations.
- Waste treatment - waste from the power plant as well as from other production activities. Waste can be treated or can be sent to a final disposal.

The development of such a general scheme, together with the identified energy systems into consideration, leads to the identification of a matrix [A], which is built up with elements a_{ij}, where i = step from the general fuel/life cycle, and j = interested energy technology and represents the base for the development of the complete comparative tool. The filling level in the matrix is associated with the corresponding complexity of the chain analysed. The matrix [A] could allow reaching different levels of information, identifying a single step in a specific chain or a complete chain.

This first part is identified as the characterisation of the technology, as shown in Figure 2.3.1.

The user of this risk comparative tool plays an active role in the whole process, and his/her intervention is requested in the initial stages. Once the user has selected the part of interest from the matrix [A], characterising the technology under investigation, then the process passes to the characterisation of the event to which the RCIs are applied.

The first step is now to define what type of event the user wants to consider. The choice comprises three possibilities, which represent the three different categories of risks concerning electricity production, previously discussed in Sections 1.3.1 and 1.3.2:

1. Risks from normal operation.
2. Risks from accidental events (routine, severe, including risks from natural disasters).
3. Risks from external non-natural events.

Subsequently, the information identified as relevant is processed through the application of the RCIs. The list of RCIs is applied, reaching a certain completeness level, differing from case to case, and directly dependent on the available information collected from external sources.

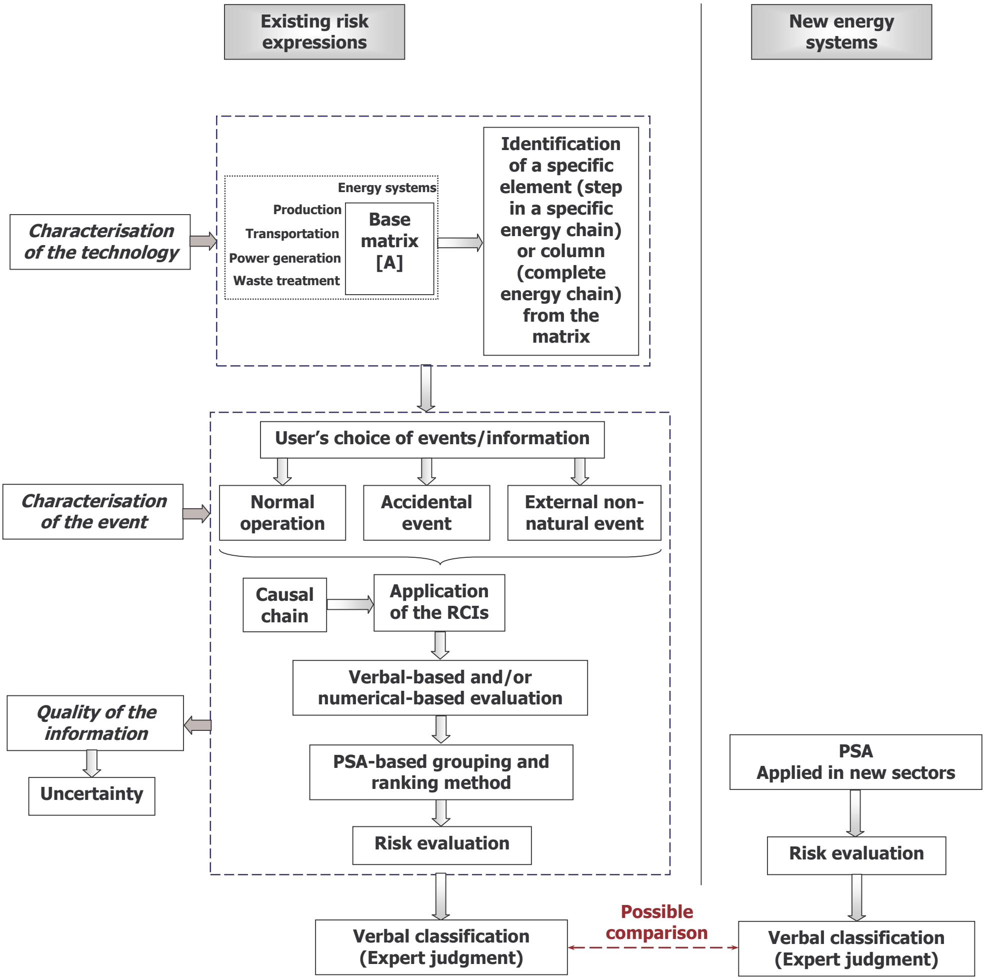


Figure 2.3.1: Framework of the whole methodology, highlighting the three processes of characterisation of the technology, characterisation of the event, and qualification of the information.

The RCIs are developed to stress important attributes of each step in the causal sequence, with the purpose to be applicable to all energy systems. They can interpret input risk information in a numerical and a verbal format. When the outcome from the RCIs is calculated, it is then available for interpretation of single indicators, or it can be processed for grouping and ranking to reach significant overall scores. This methodology offers the possibility to compare events and information at two different levels. It is possible to compare the results of single specific indicators among different cases, as well as to compare only the final overall scores. Anyhow, the purpose to reach an overall risk value would simplify the comparison across different events in different energy systems.

When dealing with grouping and ranking, the heterogeneous nature of the RCIs must be faced. This means considering that each indicator has a different meaning regarding what it represents, a different scale of evaluation, a different importance in the account of the global risk value for each specific application. To find a solution which could take care of each individuality without inserting excessive subjectivity into the process is not immediately obvious. At this stage, Boolean logic and the probabilistic risk assessment (PSA) methodology act like a rescue. Nevertheless, the application of PSA in such a context is not just an experiment, but it is naturally founded on the mathematical/physical meaning of the PSA, together with a background investigation of various multi criteria decision analysis (MCDA) methods.
The second issue concerning the lack of detailed and reliable risk information on new energy technologies is treated proposing again the use of PSA; this risk evaluation technique has been largely applied in the aerospace sector and the nuclear industry, proving its validity as a tool to evaluate risk, improve weak links, and prevent accidental events before they could happen.
The PSA methodology is a fundamental element in the development of this project, as it provides a practical instrument for use in both the problems initially highlighted. It is a flexible tool, of which the application is possible in new technological areas following the traditional approach, as well as in the context of decision making, although with limitations to be discussed.
The approach to solve the two issues that triggered the beginning of this work is thus binary. The solution of the two problems is carried on along parallel separate paths, but it must come to a common point when cross comparison is needed. Numerical results from the two methods are too different to be compared on a numerical scale. Thus, the only available solution requires passing through expert judgment.

2.4. Possible users.

The aim of this section is to identify and understand parties, which constitute possible stakeholders of the presented methodology.
Stakeholders will be defined according to their involvement in the energy sector, their activities and the possible interests that they have or represent.
The work related to the identification of the stakeholders is important to understand what aspects should be relevant in the process of development of the risk characterization indicators; aspects of interest which should make the method well accepted by the users according to their relevant interests.
It must be stressed that this identification process is just an exercise to analyze probable and possible stakeholders and their area of interest, but the discussion and the list summarized in Table 2.4.7.1 should not be seen as comprehensive of all potential stakeholders.
The stakeholders taken into account are divided into six categories: governments, non-governmental organizations (NGOs), research, commercials, citizens, and the media (mainly based on (Mallon, 2006) with some modifications). Their link with the energy risks comparative process is shown in Figure 2.4.1.

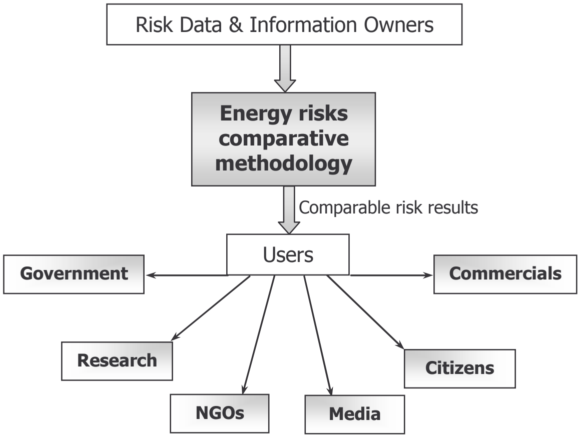


Figure 2.4.1: Link with upstream data and information owners and downstream possible stakeholders in the context of the energy risks comparative methodology.

2.4.1. Governments.

Governments and their agencies, including policy-makers and the related administration, are potential stakeholders. Governments carry on the decision-making process; they promote various energy technologies on the basis of their effects at economical, environmental and social level. Governments have to consider energy related benefits, but they also need to be aware and fairly informed about risks from energy systems. Governments are subject to political pressure and their behaviour can also reflect economical resource problems.

Governmental bodies are not limited to the national level but can also include various sub-national levels, or institutions at international level, grouping a certain number of countries under the same flag. This last is the case, for example, of the European Union, where the European Commission is one of the stakeholders interested in the use of the results provided by the use of the methodology under discussion in this thesis.

2.4.2. Non-government organizations (NGOs).

This group can refer to about any form of organization that is not a governmental institution, thus including a large number of commercial and non-commercial interest groups, with main focus on the scope they want to achieve and the interests they represent.

In its broadest sense, a non-governmental organization is one that is not directly part of the structure of a government, and can include non-profit, voluntary, business-oriented, environmental organizations, etc.

In the present investigation only energy-related and energy-interested NGOs are taken into consideration.

Organizations in favour and against certain energy technologies can be listed in this section, together with NGOs directly interested in the energy market aspects like business-related, economical and professionals NGOs.

There are also NGOs looking into sustainability aspects of specific energy systems, including the environmental effects, the social aspects of energy, including development (especially for developing countries) and the effect on local communities.

2.4.3. Commercials.

Commercials refer to legal entities, with a separate legal identity from its members, which have ordinarily the function to undertake commercial business. They are business-oriented stakeholders. They can have influence at local/regional, national or international level, according to their size and interests.

Concerning the energy sector, some companies carry on their work in a specific energy environment, while others are active participants in various energy sectors simultaneously; this is the case of industries with interest in both fossil fuels and the renewable energy technologies.

Companies from other sectors expanding their activities to the energy sector also need to be taken into account. This is the case of some major photovoltaic actors previously working in electronics.

Not only energy suppliers, manufacturers, developers, generators should be listed. Also finance, insurance and investments companies should be mentioned in this section, as they are dealing with the economical aspects of energy and they could be interested in understanding possible risks.

Finally, there are also other commercial parties which can be interested, as possibly affected, by many aspects of the energy technologies, like intensive energy users (energy availability), farmers (land use and facilities siting), etc.

2.4.4. Research.

The research area includes any kind of research institution aimed at public or private research. Universities, research institutes, and industrial research centres, at national and international level, are possible stakeholders in this group.

The research departments interested in energy risks are involved in topics that can vary from energy studies, including energy development and energy industrial processes, to areas like epidemiology, safety, environment, sustainability, etc.

2.4.5. Citizens.

People are affected by energy systems and their development in different ways. First of all they take advantage of the benefits of power supply, job opportunities, and financial investments. On the other side, they are also concerned by possible human, environmental, and economical hazards emerging from energy technologies per se, their specific location, the occupational safety issues in the work environment, etc. Sometimes the subjective risk perception based on bad, incomplete, incoherent, or misleading information can result in biased or even wrong conclusions concerning actual risk levels.

To allow a fair risk evaluation, it is important that people are informed in a clear and easily understandable way, which is the primary objective of the whole methodology of risks comparison.

Moreover, people can act with a great influence at local, regional or national levels, involving the media and affecting political decisions and planning processes.

2.4.6. Media.

This is an important stakeholder as it mediates and influences the interactions between all stakeholders, acting not only as a conduit of information, but also affecting opinions. Media

are the first channel of information for the vast majority of people, not only through newspapers and magazines, but also through television and internet.
In a world where the energy technologies and the energy market play a fundamental role in the society, economy, and policy, having media able to evaluate risks in a fair way providing appropriate comments and conclusions is really important.

2.4.7. The stakeholder matrix.

After the analysis of the different groups of stakeholders, a summary matrix (Table 2.4.7.1) provides an overview of the potential types of users identified for each category previously discussed. The matrix highlights the possible interests of each group, and their benefits in return when using the proposed method of risks evaluation.
The stakeholders listed in Table 2.4.7.1 are not acting-alone entities, but there are numerous mutual relations among them. Of all stakeholders, the media play a fundamental role as they are pervasive to all other sectors.
Research in the area of risk perception demonstrated that people rank risks not only on scientific studies of the probability of harm, but also on personal perception of how well the process is understood, its relation with cancer, the degree of catastrophe, the impartiality of danger distribution, the individual control level to exposure, and whether risk is voluntary or imposed (Liverman, 2001).

Table 2.4.7.1: The matrix of possible stakeholders, with identification of some example (Colli et al., 2005-b).

	Who they are		What interest they have or represent	What the complete energy risks comparative methodology can do for them
Stakeholders	**Identification**	**Possible types**	**Possible interests**	**Added value from the method**
Government	Government at all levels and government-related activities	Policy makers (councils, authorities, agencies, departments), administration	Decision making process (economically, environmentally, socially). Formulation of the agenda for energy-related issues, formulation and implementation of the policy program, and evaluation of actions	Better understanding of risk aspects to make political choices and their implementation

NGO	Commercial and non-commercial interest groups	NGOs for energy (different type related, pro and con), business, economy, environment, social and conservation, professional, development, and educational purposes	Energy knowledge, development and effects of energy related activities on business, economy, environment and society	Better knowledge of energy safety aspects, and better understanding to support political choices and their implementation
Commercial	Commercial stakeholders	Individual and massive trans-national commercial entities (finance companies, insurance companies, institutional investors, manufacturers, suppliers, developers, generators, energy-intensive users, farmers)	Risk perception, safety, and security of supply	Risk perception facilitation, and better understanding of risk aspects from fair comparison
Research	Institutions for public and private research	Academic centres, research institutes and industrial research centres	Research departments of energy, epidemiology, safety, environment, sustainability	Easy accessibility of data for evaluations, better understanding of risk aspects from fair comparison
Citizen	Acting-alone individuals	People concerned or affected by human, environmental and economical impacts. Examples are site holders, individual investors, project contractors, employees	Energy availability, risk perception	Risk perception facilitation, and better understanding of risk aspects from fair comparison
Media	Conduit of information	Television, newspapers, magazines, internet	Survey and information delivery	Better understanding of risk aspects from fair comparison

To examine this process, Kasperson (Kasperson et al., 1988) investigated the concept of the social amplification of risk, suggesting that the actions of the media, government, and non-governmental organizations, as well as disputes among scientists, can significantly increase or decrease public risk concerns.

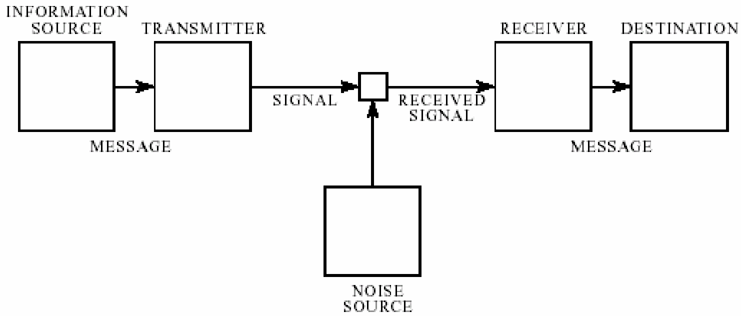


Figure 2.4.7.1: Schematic diagram of a general communication system as from (Shannon, 1948).

When talking about communication, an immediate comparison, which highlights many similarities, can be done with the mathematical theory of communication. Also in this case the fundamental problem is to reproduce a piece of information, in the form of a signal, from a point to another, either exactly or approximately.

From the physical perspective, a communication system, as indicated in Figure 2.4.7.1, consists of the following five essential parts (Shannon, 1948):

1. An information source, which originates the message to be communicated to the receiving terminal.
2. A transmitter, which operates on the message to make it suitable for transmission over the channel.
3. The channel, which is the medium used to transmit the signal, but can also introduce distortion and random noise to disturb the signal.
4. The receiver, with the duty to reconstruct the original message from the received signal.
5. The destination, representing a person or a device, to which the message was addressed.

This sequence of elements originated in a mathematical context corresponds to the following elements in the area of risk communication:

- Information source → is a specific risk event, as seen and reported.
- Transmitter → is the collection and elaboration of information concerning a specific risk event to allow communication. For example, it can be a risk report, collecting all information about the chosen event, or the related data stored into a database.
- Channel and noise source → the communication pathways are oral, written or visual. When communicating risk through media or other channels (letters, telephones, direct conversations, etc.), the information can be affected by noises (different opinions and judgments, wrong or modified information, etc.) and receiving modifications and distortions.
- Receiver and destination → these two elements represent the audience of risk communication, which can be very wide and can group all stakeholders mentioned in Table 2.4.7.1.

Noise is supposed to enter this communication chain through the channels of communication's flow, but it is important to note that every step is somehow affected by the subjectivity of involved actors.

Moreover, after receiving and elaborating the risk information, the communication system originates a feedback, which can affect both the source/transmitter part, and the channel (Pidgeon et al., 2003).
According to what is hypothesized in (Kasperson et al., 1988), the key risk amplification steps are the following:

- Filtering of signals, which means that only part of the incoming information is processed.
- Decoding of the signal.
- Processing of risk information, using knowledge, sometime affected by subjective view.
- Attaching social values to the information, with a management and policy perspective.
- Interacting with one's cultural and peer groups, to have a valid interpretation and validation of signals.
- Formulating behavioural intentions to tolerate the risk or to act against it.
- Engaging in group or individual actions to accept, ignore, tolerate, or change the risk.

With view to the risk perception and risk amplification context, the correct knowledge, as much as possible corresponding to the reality of the situation, of every stakeholder is important, in a way that it can influence the thought of others. The point of view of the stakeholders in the energy environment can be fundamental to amplify or dampen perceptions of risk and, through this, create secondary effects such as stigmatization of technologies, economic losses or regulatory impacts. Both social and individual factors can act to determine the social perception of risk, and in this framework a good communication is of great importance (Pidgeon et al., 2003).
It is clear that stakeholders, with their perception, can determine, with different degree of influence, the success or failure of projects related to specific energy technologies. Stakeholders can also influence the economical support, the actions taken towards or against, the acceptance, and many other aspects of a certain energy system. Thus it is important that they are informed in a fair and comprehensive manner, to acquire the right knowledge to support their judgment.

2.5. References.

(Colli et al., 2005-a) - A. Colli, A.L. Vetere Arellano, C. Kirchsteiger, "Development of a General Scheme for Fuel Cycles and Life Cycles from all Energy Technologies as a Basis for the European Energy Risk Monitor (ERMON)", EUR 21735 EN, Publication of the European Commission Joint Research Centre, Petten, The Netherlands, 2005.

(Colli et al., 2005-b) - A. Colli, C. Kirchsteiger, A.L. Vetere Arellano, B.J.M. Ale, "Methodology Based on Indicators for Comparison of Risks Results from Different Energy Systems", Annual Conference of the Society for Risk Analysis – Europe 2005, Major Risks Challenging Publics, Scientists and Governments, 12-14 September 2005, Politecnico di Milano-Polo di Como, Como, Italy.

(Gray, Wiedemann, 1999) - P.C.R. Gray, P.M. Wiedemann, "Risk Management and Sustainable Development: Mutual Lessons from Approaches to the Use of Indicators", Journal of Risk Research 2 (3), (1999), pp. 201-218.

(Kasperson et al., 1988) – R.E. Kasperson, O.M. Renn, P. Slovic, H.S. Brown, J. Emel, R. Goble, J.X. Kasperson, S. Ratlick, "The social amplification of risk: a conceptual framework", Risk Analysis 8(2): 177±87, 1988.

(Liverman, 2001) – D. Liverman, "Environmental Risk and Hazards", International Encyclopedia of the Social Behavioral Sciences, Elsevier, 2001, http://www.eci.ox.ac.uk/~dliverma/CV/HazardsIESBS.pdf .

(Mallon, 2006) – K. Mallon (Editor), "Renewable Energy Policy and Politics", Earthscan, 2006, ISBN 1-84407-126-X.

(Pidgeon et al., 2003) – N. Pidgeon, R.E. Kasperson, P. Slovic, "The Social Amplification of Risk", Cambridge University Press, 2003, ISBN-10: 0521817285.

(Shannon, 1948) – C.E. Shannon, "A Mathematical Theory of Communication", from The Bell System Technical Journal, Vol. 27, pp. 379–423, 623–656, July, October, 1948.

(Stern, Fineberg, 1996) - P.C. Stern ,H.V. Fineberg (Eds.), "Understanding risk: informing decisions in a democratic society", National Academy Press, Washington D.C., 1996.

PART II

The methodology

3. Fuel cycles and life cycles: the general chain and the base matrix.

The work presented in this chapter is extracted from (Colli et al., 2005), although minor changes are introduced.

3.1 The energy flow.

To generate useful power, for example electricity, a source of primary energy is required. An energy source is a primary resource, a substance or natural phenomenon, which can be converted through chemical, mechanical, or other means, to supply energy, in the form of heat or electricity, as well as intermediate energy carriers, such as hydrogen. Energy sources include coal, petroleum, natural gas, water movement, uranium, wind, sunlight, geothermal, and other sources.

An energy carrier is simply any substance used to transfer energy from the place of production to the place of use. For example, if energy from a nuclear power plant is used to produce hydrogen by electrolyzing water, and later hydrogen is burned in a fuel cell to drive a car, then hydrogen is the energy carrier moving energy from uranium to the vehicle.

It is clear at this point that energy is converted from one form to another. Energy is not destroyed. Anyhow, different energy systems have different ability to perform work, and thus the quality of their energy output is different. Due to the irreversibility of the conversion process to transform energy from one type to another, part of the energy is unusable, and ends up increasing the entropy of the surrounding universe. Physics tells us that there is a process of degradation of energy, directly connected to the loss of extractable work from a system (Mazzoldi et al., 1991). In the energy conversion process there is then a loss of exergy (Pedrocchi & Silvestri, 1991). With reference to the second law of thermodynamics, exergy is defined as available energy, the maximum amount of work that can be extracted from a physical system by exchanging matter and energy with large reservoirs in a reference state (normally the surrounding environment or ambient as reference for the thermodynamic state properties). While energy is conserved, exergy can be destroyed. While there is a constant amount of energy in the universe, the amount of exergy is constantly decreasing with every physical process according to thermodynamics second law. The concept of exergy can be used as a reliable index to indicate the quality of energy sources and also to evaluate the in- and out- flows of a fuel cycle, qualifying the energy output (Szargut, 2005).

The concept of exergy is important, as it allows the evaluation of the quantity of energy needed at input, to obtain a certain energy output. In fact, exergy quantifies and qualifies the losses of energy that take place when performing a certain process.

A schematic view of the transformation of various energy sources into electricity (another form of energy) is described in Figure 3.1.1.

The chain of processes leading from the identification of an energy source to its transformation into a useful form of energy is described by a fuel cycle. A fuel cycle considers all the steps of the fuel transformation, starting from extraction, passing through transportation, to use in the power plant, and finally to waste treatment and waste disposal. As an example, Figure 3.1.2 shows the various stages of the nuclear fuel cycle.

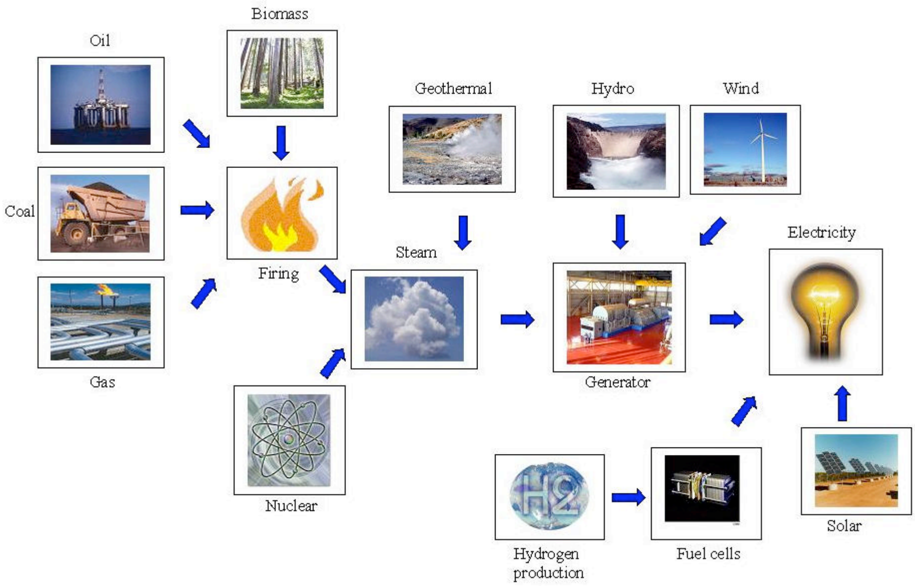


Figure 3.1.1: Schematic view of electricity generation from various sources (Colli et al., 2005).

The life of the technologies - from design, to construction, use, and decommissioning -, which practically allow the transformation of energy sources into useful energy, is described by a life cycle. As an example, Figure 3.1.3 depicts the stages of the photovoltaic modules life cycle.
Fuel and life cycles do not exist as isolated entities, but they are connected to each other, and their combination represents the total energy supply cycle, as shown in Figure 3.1.4.
Thus, the total energy supply cycle is the union of one or more fuel cycles (considering that some power plants can be fed by different energy sources) and one ore more life cycles (considering, for example, the presence of a power plant and other possible facilities, such as refinery in the oil chain), which is important in order to obtain a complete description for assessing a specific situation.
Given the similarity in the path of fuel and life cycles, after investigation of various examples from different energy systems, it is possible to formulate a general scheme, adaptable to the various cases. This general chain is discussed in details in the next section.

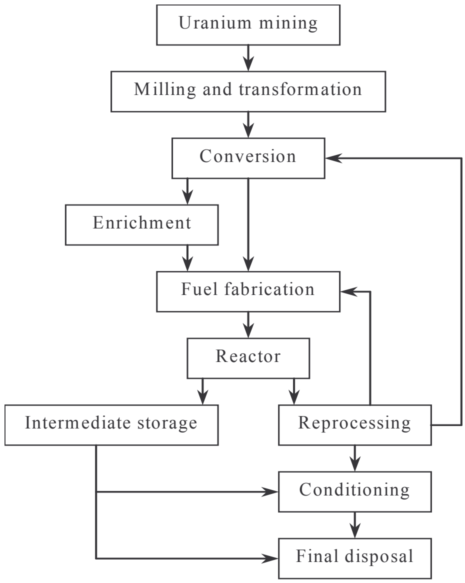


Figure 3.1.2: Stages of the nuclear fuel cycle considered for Germany in ExternE, Externalities of Energy (ExternE, 1999), a research project of the European Commission, the first comprehensive attempt to use a consistent 'bottom-up' methodology to evaluate the external costs associated with a range of different fuel cycles.

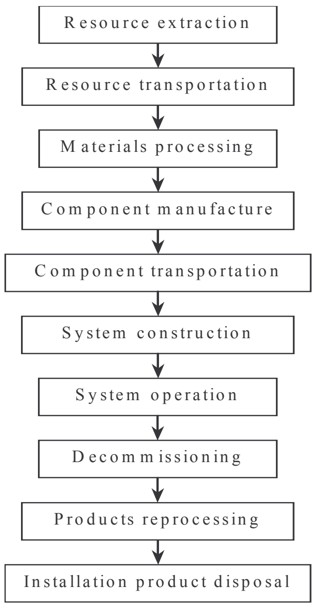


Figure 3.1.3: Steps of the photovoltaic module life cycle as modelled on the base of (ExternE, 1999), [1], [2].

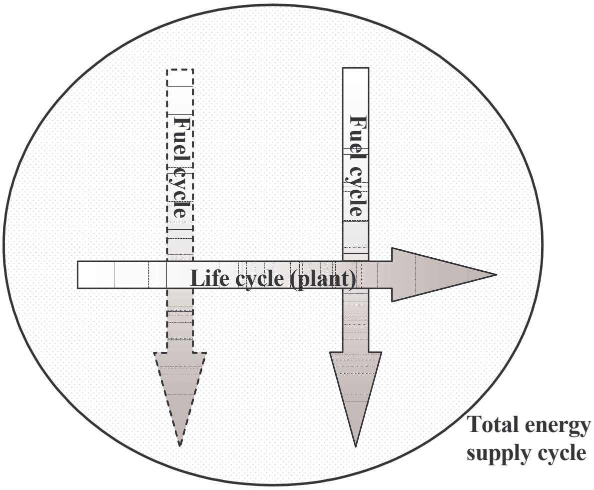


Figure 3.1.4: Representation of the concepts of fuel cycle, life cycle and total energy supply cycle (Colli et al., 2005). The dashed fuel cycle arrow represent the case when a power plant could be fed by different fuels, thus involving more than one fuel cycle. In a total energy supply cycle view, normally more chains are normally involved. Beside the fuel cycle, various life cycles could be also considered, representing the life of involved installations and technologies, e.g. the plant life cycle reported in the figure.

3.2 Specifications of the general scheme for fuel and life cycles.

The previous investigation of various paths connected to the transformation of energy sources and energy carriers into useful energy, such as electricity, has led to identify similarities and to formulate a general scheme adaptable to all fuel and life cycles, shown in Figure 3.2.1.

The scheme is represented by four main steps:

1. Production - related to all the operations of production of the subject into analysis (it can be production of a fuel, as well as a component or a material).
2. Transportation - including the operation of transport of raw material, final product or waste. Storage has been considered as a part of the transportation stage, as the stored material is in fact waiting to be transferred to another intermediate place or to the place of use.
3. Power generation – referring to the power plant, including the plant installation and the onsite transmission and distribution facilities.
4. Waste treatment - the final step in the chain, receiving wastes from the power plant, as well as from other production activities. Wastes can be treated or can be sent to a final disposal.

These four main stages are then divided into corresponding sub-steps of first and second level, to obtain a clearer characterisation of the chain.

The sub-steps of first level for production are:

- Exploration – it is the procedure that allows to locate the resource or to identify the geographical location where is very likely to find it. This step mainly includes geographical and geological investigations.

- Extraction – it is the process to make the resource available for next transformation or use. Activities like mining, drilling or collecting are included in this phase.
- Treatment – it is the step in which the final product to be used, that can be a fuel or a component, is prepared, or in some cases created, and made available for direct use or for transportation. This stage includes steps such as petroleum refinery, as well as purification, compression or liquefaction of natural gas, biomass residue processing or bio-fuels production, as well as photovoltaic modules manufacture or wind turbine manufacture.

Transportation is further divided into sub-steps of first and second level, which are:

- Raw material transportation – it is the link between extraction and treatment of the resource.
- Transportation – it considers the movement of a certain product according to various distances, and it is further divided into:
    - Long distance transportation – transportation between different countries or different continents. This step can include high pressure natural gas pipeline, as well as oil barge transportation.
    - Regional distribution – it is transportation between different regions of the same country.
    - Local distribution – it is a local transportation, mainly restricted to the area of use. Pipeline transportation mainly includes low pressure pipeline at this stage.
- Waste transportation – it is the transportation of waste which can be generated at different levels in the chain. For example, nuclear waste can be transported in special container.
- Storage – it can be considered a stand-by location for the product, and it can be classified as:
    - Material storage – it is the storage before material or fuel use. Part of this stage can be the hydro reservoir, the storage of hydrogen in pressure or insulated tank, the storage of nuclear fuel in special container or in the nuclear power plant.
    - Waste storage – this can be in the place where wastes are generated or constitute an intermediate storage location before final waste disposal.

Power generation is also further divided into sub-steps of first and second level, which are:

- Fixed installation:
    - Construction – this stage includes all the operations of preparing the area of construction and building the power plant or an energy technology.
    - Operation – it is the operative part, including functioning and maintenance for the power generation.
    - Dismantling – groups all the operations of dismantling the installation and bringing the area in the same environmental conditions as before. Material recycling and disposal related to the power installation are also included in this step. Dismantling procedures can be very expensive, like for nuclear power plant, and the monetary resources necessary for the operations are gathered during the lifetime of the installation.

- Transmission/distribution facilities – this step includes all the facilities (pipeline, cable, etc) for heat and electricity transmission and distribution.

The sub-steps of first level for waste treatment are:

- Waste reprocessing – includes the operations of recycling materials or fuels (e.g. nuclear fuel), or treating wastes to reduce their hazardousness.
- Waste disposal – is the final allocation of wastes in landfills or in dedicated deposits.

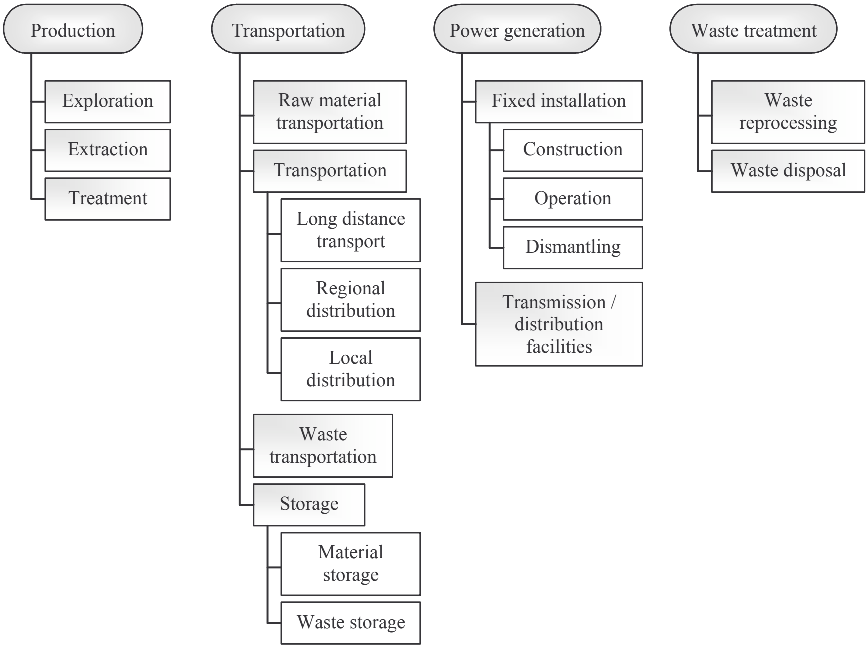


Figure 3.2.1: Stages of the general scheme for fuel and life cycles (Colli et al., 2005).

It must be stressed that this general chain is developed in such a way that every fuel or life cycle can find the allocation of its own steps in it, but the fulfilment of all steps at once is not a requirement, also from the point of view of the energy risk comparative methodology in argument in this thesis. The following section will clarify the use of the general chain within the methodology under discussion.

3.3 The base matrix for the energy risk comparative methodology.

The general chain shown in Figure 3.2.1 and presented in details along the previous section serves as a basement to support the following developments of the methodology based on indicators to compare risk from different energy systems.

Such a chain, in combination with the different energy systems which could possibly be part of a specific application, defines the structure of a matrix [A], done by elements a_{ij}, where i = step from the general chain, and j = interested energy technology.

Figure 3.3.1 shows an example of how the matrix is used. Its main scope is to initially identify the area of comparison and thus locate the events to be compared, to understand the technological context in which they took place (e.g. it could be an explosion in a long distance transport pipeline, or an explosion affecting raw material transportation).

Matrix [A]

	En. sys. 1	**En. Sys. 2**	**En. Sys 3**	**...**
Production	a_{11}	a_{12}	a_{13}	…
Transportation	a_{21}	a_{22}	a_{23}	…
Power generation	a_{31} =event 1	a_{32}	a_{33} =event 2	…
Waste treatment	a_{41}	a_{42}	a_{43}	…

Type: E.g. explosion 2
Information: Risk assessment 2
Indicators: Numerical/verbal application results (set 2)

Type: E.g. explosion 1
Information: Risk assessment 1
Indicators: Numerical/verbal application results (set 1)

Figure 3.3.1: This picture offers an example of how the base matrix [A] works, listing only the four main steps of the general chain for practical reasons. Every risk-related event in the energy context is identified by the energy system and the step of the chain to which it belongs. In reverse, every element of the matrix is connected to specific events, for which information is available. In this case, only elements a_{31} and a_{33} are associated to selected events, thus they are the only elements in the matrix containing information. The information is then processed through a set of risk indicators to be comparable with other cases under observation.

There is also a practical issue underlying the use of such a matrix. Let us consider the chance that this methodology could be applied for practical use, for example as a computer-based tool relying on a wide database of energy risk information. At that point, the matrix will be the first interface with the database. Selecting a specific element of the matrix will create a link to a previously specified set of events, limiting the selections in the database. Further, more specific event selection criteria should be entered.
But this is not the only reason to support the use of this matrix. Later on in this thesis, when discussing about the limitations in the possibility of comparison among energy systems, the role of the step of the chain becomes important in the identification of the similarities among the events.
The filling level in the matrix is associated with the correspondent complexity of the chains into analysis and the number of stages to consider; this means that some chains could cover, according to their complexity, all or almost all the steps and sub-steps of first and second level indicated in Figure 3.2.1 (for example, the nuclear chain or the fossil chains), while other chains could cover only a little number of those steps (for example, the wind energy chain). This number of stages could be also further limited by the selective interest of the stakeholders or by the unavailability of data and information to process. The matrix [A] could allow reaching different levels of information, identifying a single step in a specific chain or, if needed, a complete chain.

3.4. References.

(Colli et al., 2005) - A. Colli, A.L. Vetere Arellano, C. Kirchsteiger, “Development of a General Scheme for Fuel Cycles and Life Cycles from all Energy Technologies as a Basis for the European Energy Risk Monitor (ERMON)”, EUR 21735 EN, Publication of the European Commission Joint Research Centre, Petten, The Netherlands, 2005.

(ExternE, 1999) – "ExternE, Externalities of Energy", Vol. X: National Implementation, a Research Project of the European Commission, prepared by CIEMAT, ES, 1999, http://www.externe.info/

(Mazzoldi et al., 1991) – P. Mazzoldi, M. Nigro, C. Voci, “Fisica”, Società Editrice Scientifica, ISBN 88-7790-047-3, 1991.

(Pedrocchi & Silvestri, 1991) – E. Pedrocchi, M. Silvestri, “Termodinamica tecnica. Introduzione”, edizioni Città Studi, ISBN 88-251-7030-0, 1991.

(Szargut, 2005) – J. Szargut, “Exergy Analysis”, Academia, the magazine of the Polish Academy of Science, No. 3(7), 2005, http://www.english.pan.pl/index.php?option=com_content&task=category&sectionid=28&id=110&Itemid=182

[1] - http://www.ecoinvent.ch/

[2] - http://www.nrel.gov/solar/

4. Modelling on the base of the causal sequence for energy systems.

4.1. The causal sequence for energy systems.

Energy technologies cover a wide range of systems, different per adopted primary energy source, equipments, machineries, processes, etc.
To uniform the approach of risk investigation in such a broad area, it is necessary to use a model, which can be easily adapted to different energy processes, and can unify their main characteristics under the same structure. The choice is the causal model.
The concept of causality is a greatly-discussed philosophical concepts that can be traced back, in the western tradition, to Aristotele. The notion of causality indicates a cause-effect relationship, a necessary connection between and event and its consequence. A causal chain links a series of those relationships. Actually, it is a ordered sequence of events or actions, where every step is the effect of the previous one and the cause of the next one.
Thus, a proper causal chain has the capability to order the sequence of energy-related hazard development in a form adaptable to all energy systems. In a later moment, indicators to characterize each step of the causal structure will be introduced.
The approach passing through a causal categorization using a causal model to study hazards progresses has been developed at CENTED (Center for Technology, Environment and Development) at Clark University in the 1980s by a team including C. Hohenemser, R.E. Kasperson, R.W. Kates (Hohenemser et al., 1985). This model describes the development of hazards as a chain of cause/effect related steps, from human need or want, further evolving into a series of occurrences and consequences that can cause harm to human beings or damage what they value. The causal sequence originally presented by (Hohenemser et al., 1985) is composed by seven stages: human needs, human wants, choice of technology, initiating events, outcomes, exposure, and consequences. The initial purpose of this model was to assist in the comparison of various technological hazards. Later, it was also adapted to a large number of applications, including the comparison of environmental hazards (Kasperson & Kasperson, eds, 2001).
An approach based on using a causal sequence is also suggested for the prevention and the mitigation of hazards associated to the use of dangerous chemical substances in photovoltaic manufacturing facilities (Fthenakis, 2001). The proposed structure identifies six sequential steps of hazard development. Its main purpose is identifying layers of prevention and mitigation, offering the possibility to highlight the points of intervention along the causal chain to mitigate hazards before they further develop.
The definition of a causal structure for energy systems, which can be used as a fundament for the risk comparative methodology based on indicators, thus for the purpose of this thesis, takes into account the first model developed by (Hohenemser et al., 1985), and a further model adopted in (Hohenemser et al., 2000) to study technological hazards. The resulting causal sequence for hazards development for energy systems is presented in Figure 4.1.1.

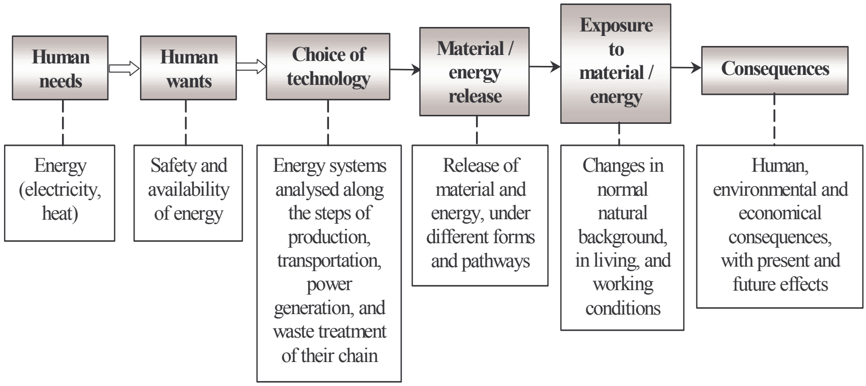


Figure 4.1.1: The causal structure of energy systems (Colli et al., 2008).

This model of hazard causation anchored at one end on human needs, and at the other on consequences, linked through a causal sequence of steps. Human needs and human wants generate energy-related activities, which can produce changes in material/energy fluxes, originating releases; these releases induce some exposure, which could have some consequences on people and things that they value, as well as on the environment.

In the context under investigation, human needs refer to the possibility of using energy, mainly in the form of electricity, for personal well-being, societal growth, or industrial activities.

The choice of the technology is then linked to the identification of the specific energy system into analysis, evaluated along its complete fuel/life cycle or the steps of interest. According to the chosen system, specific events could originate and generate a release of material or energy according to different modalities, forms and pathways. This release is going to change the usual natural background, against which the level of exposure is defined, leading then to specific human, environmental, and economical consequences.

The causal classification clearly delineates the sequence of events that leads to accidental situations, and it is also a support for discovering available points for intervention useful in the process of hazard management. In this way it is possible to define control actions and barriers that aim to block the evolution of the causal development of a certain hazard, defining also implementation modes to facilitate their adoption (Kates & Kasperson, 1983).

Each link in this chain may be described by some specific characteristics. Each characteristic may then be described by a measurable indicator (expressed by some numerical scale). Finally, specific indicators could be identified at different stages in the causal structure, characterizing each step of the process.

4.2. Example set of indicators.

Once the causal structure is defined, giving the line of evolution for energy-related hazards, it is then the moment to look for the convenient way to characterize every step in a measurable way.

A very good set of indicators to start with, always developed on the backbone of a causal chain, is offered by C. Hohenemser, R.W. Kates and P.Slovic in their work "The nature of technological hazard" (Hohenemser et al., 2000). The study investigates technological hazards and their evolution as a sequence of causally connected events. The supporting

causal sequence is very close to the chain adopted along this thesis and shown in Figure 4.1.1. The path of technological hazards involves potentially harmful releases of energy and materials, leading from human needs and wants, to the choice of the technology and to the consequences caused by the specific release and the exposure to energy and/or material.
The work discussed in (Hohenemser et al., 2000) defines and presents twelve measures, expressed in the form of twelve indicators, to be applied at the appropriate step in the causal chain (Figure 4.2.1). The twelve indicators have significant characteristics that are applicable to all sorts of technological hazards. Moreover, they are expressed in common units, which facilitate understanding to non-experts.

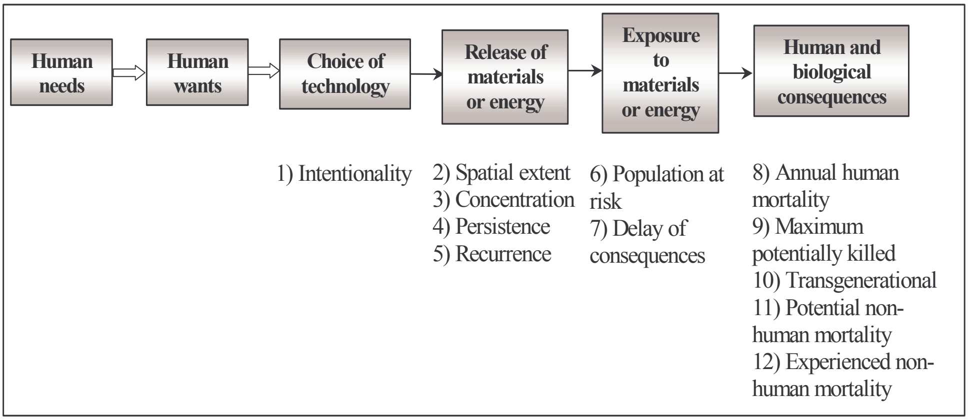


Figure 4.2.1: Causal structure and set of indicators as presented in (Hohenemser et al., 2000).

Some indicators are numerically quantified by a categorical distinction, like intentionality, transgenerational, potential non-human mortality, and experienced non-human mortality. The remaining indicators (spatial extent, concentration, persistence, recurrence, population at risk, delay of consequences, annual mortality, and maximum potentially killed) are evaluated using a logarithmical scale. In (Hohenemser et al., 2000), the choice of a logarithmic scale is preferred as allowing a representation with the quality of matching human perception better than a linear scale (e.g. this is also the case of the decibel sound intensity scale or the Richter earthquake intensity scale).
The indicators listed in Figure 4.2.1 focus on various features of hazardousness for technological systems. They are hazard indicators. Few of them, like for example annual human mortality, can find some connections to the risk field. Nevertheless, they do not consider the probabilistic approach needed to evaluate risk. When considering this example set of indicators to develop our set of RCIs, this difference must be taken into account, and composition with probability has to be introduced.
As in this context the purpose is only to briefly introduce the methodology adopted as background for the development of the set of RCIs, for any deeper investigation of the model here introduced, and the related indicators and scoring system, it is suggested to refer to (Hohenemser et al., 2000).

4.3. Reasons of the choices.

The choice of the causal model as supporting structure for the development of the risk comparative methodology based on indicators has its primary motivation in the high level of adaptability of the model itself, which allows applications to different cases and situations for various energy systems, in a unique and for each system identical construction. It is a versatile approach, able to cope with different kinds of hazard evolutions, which, in their turn, have also different kinds of associated characteristics (e.g. radiological effects of nuclear installations vs. health/environmental impact of chemical substances used in the oil industry).

The further possibility to associate indicators to each step of the causal model allows expressing energy risk characteristics in common units, thus easier to understand for non-expert in risk studies. Moreover, the indicators, as specified in the work discussed in (Hohenemser et al., 2000), can evaluate not only numerical information, but also categorize other sources of information (e.g. verbal information) according to a predefined scale. This is an important added value when dealing with risk expressions, as they can be numerical or they can have a more qualitative form, such as a verbal statement.

4.4. References.

(Colli et al., 2008) - A. Colli, A.L. Vetere Arellano, C. Kirchsteiger, B.J.M. Ale, "Risk characterisation indicators for risk comparison in the energy sector", Safety Science, 47 (1), pp. 59-77, Elsevier, Jan 2009, http://dx.doi.org/10.1016/j.ssci.2008.01.005

(Fthenakis, 2001) – Fthenakis, V.M., "Accident Prevention and Hazard Management for Photovoltaic Manufacturing Facilities", NCPV Program Review Meeting Proceedings, Lakewood, Colorado, 14-17 October 2001, http://www.nrel.gov/ncpv_prm/pdfs/papers/128.pdf

(Hohenemser et al., 1985) - C. Hohenemser, R.E. Kasperson, R.W. Kates, "Causal Structure in Perilous Progress: Managing the Hazards of Technology", Boulder, CO: Westview Press, (1985).

(Hohenemser et al., 2000) - C. Hohenemser, R.W. Kates, P. Slovic, "The Nature of Technological Hazards", chapter 10 from the book: "The perception of Risk. Risk, Society and Policy", P. Slovic editor, Earthscan, (2000).

(Kasperson & Kasperson, eds, 2001) - J.X. Kasperson and R.E. Kasperson editors, "Global Environmental Risk", United Nations University Press, (2001).

(Kates & Kasperson, 1983) – R.W. Kates, J.X. Kasperson, "Comparative Risk Analysis of Technological Hazards (A Review)", Proc. Natl. Acad. Sci. USA, Vol. 80, pp. 7027-7038, November 1983.

(Liverman, 2001) - D.M. Liverman, "Environmental Risks and Hazards", pp. 4655-4659 in N.J. Smelser and P.B. Baltes (Eds.) "International Encyclopedia of the Social Behavioral Sciences", Pergamon, Oxford, 2001, http://www.eci.ox.ac.uk/~dliverma/CV/HazardsIESBS.pdf

5. The Risk Characterisation Indicators (RCIs).

5.1 On the road to developing and evaluating the RCIs.

Starting from the sample set of indicators discussed in the previous Chapter 4, the list has been implemented and modified to better fit the risk characteristics of the energy systems.
To establish a useful set of indicators to typify risk, various inputs have been considered from the investigation discussed in the previous chapters (see Figure 5.1.1).
The appropriate knowledge of a wide group of energy systems, along with the investigation of their fuel/life cycles, has a fundamental importance. Energy technologies cover a wide range of systems, different according to adopted primary energy source, equipments, machineries, processes, etc. Energy systems, their characteristics, and their expected risk scenarios are analysed. This prior investigation leads to the identification of what the indicators should represent, with respect to importance and risk significance. In addition, the possible available data and information to be used should be also taken into account, which dictate the investigation level of the indicators. Finally, but not less important, is the consideration of the possible stakeholders, and their needs.

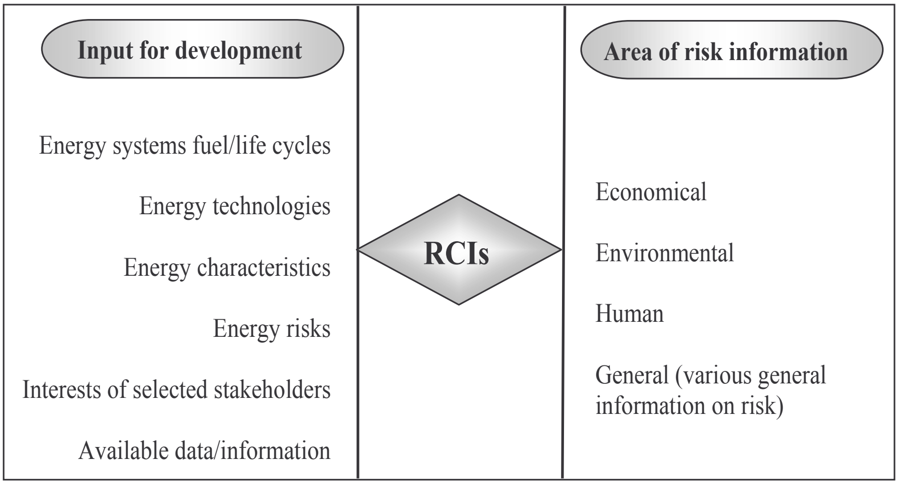


Figure 5.1.1: Inputs used for the development of the RCIs, and areas of risk information covered by the indicators (Colli et al., 2008a).

The outcome is a new, enhanced set of indicators, which highlights relevant aspects of risk affecting different energy systems: these are the Risk Characterisation Indicators (RCIs).
The original base set of indicators from Hohenemser, Kates, and Slovic (Hohenemser et al., 2000) has been created to deal with technological hazards, thus it is focused on the outcome, that is on the consequences of possible dangerous situations.
With the RCIs we want to make a step further and want them to deal with risk. Thus they have to take into consideration, in their final output, the consequences of an energy-related

event in combination with the associated probabilities. The need to introduce probability concepts is called by the circumstances of the specific context of this work, as the aim is developing a methodology for performing a comparison of risks.
The evaluation of the probabilities follows the path offered by the Bayesian theory, as explained in Section 5.6 at the end of this chapter. Nevertheless, assumptions could be introduced when no sufficient information is available.
Once developed, the RCIs are expected to cover the three usual areas of risk – economical, environmental, and human – adding also other general information of interest.

5.2. Proposed set of RCIs, with additional associated descriptors.

The elaboration and refinement of the original set of indicators from (Hohenemser et al., 2000) has led to the new modified set of RCIs, as shown in Figure 5.2.1. A total of seventeen indicators have been listed, introducing typical aspects of energy systems, covering the different areas of human, environmental, and economical risk.

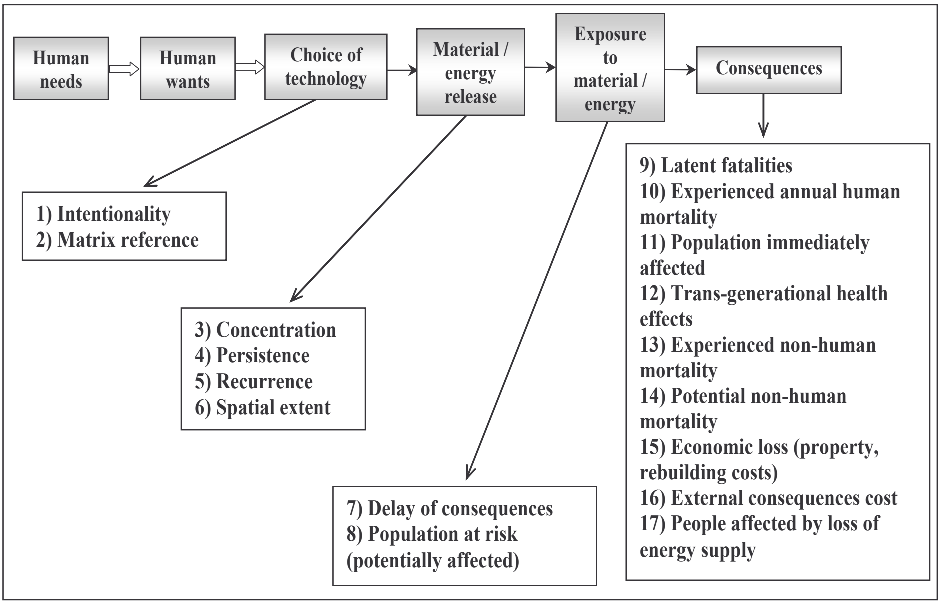


Figure 5.2.1: Causal structure for the development of energy-related hazardous events, and the associated set of RCIs (Colli et al., 2008b).

The RCIs identified in Figure 5.2.1 are linked to the corresponding step of the causal chain for energy systems, which helps to recognize the area of investigation in the hazard development chain. The same link is also available in the first column of Table 5.2.1, where the RCIs are presented along with their definition and sub-classification.
All the indicators are identified by a code. Each code recalls the reference step in the causal chain to which the indicator is connected. They have the function to facilitate the use of the RCIs during their processing in the comparison of energy risks

Table 5.2.1: RCIs classification table.

Step in the causal chain	**Indicator identification code**	**Indicator**	**Definition**	**Sub-classification**	**Area of risk (only for core RCIs)**
Choice of technology	CT-01	Intentionality	Definition of the level of intentionality of the event into analysis, distinguishing between accidental event, external non-natural event, and normal operation.	Accidental event External non-natural event Normal operation	-
	CT-02	Matrix reference	Identification of an energy system through one step of its fuel or life cycle, or in total. It defines the element aij (energy system and step of chain) or the column (all chain) of the matrix [A]. i= step of the general chain. j= identified energy system.	Element Column	-
Material/energy release	MER-01	Concentration	Concentration of released energy or materials, relative to a threshold considered significant.	Material Energy Nuclear radiation	General
	MER-02	Persistence	Time over which a release remains a significant threat to humans.		General
	MER-03	Recurrence	Mean time interval between releases above a minimum significant level.		General
	MER-04	Spatial extent	Maximum distance over which a single event has significant impact. The results are divided between internal (if not affecting areas outside the border of the involved facility or property ground) and external (with specific numerical division on the distance).	Internal External (numerical division)	Environmental
Exposure to material/energy	MEE-01	Delay of consequences	Delay time between exposure to hazard release and occurrence of consequences.		General
	MEE-02	Population at risk (potentially affected)	Maximum number of people potentially affected by the hazard (e.g. under worst conditions).	Occupational Non-occupational Global value (as total if the distinction is not available or clear)	Human

Consequences	C-01	Latent fatalities	Number of people affected by latent effects. The latent fatalities are represented by the sum of late and delayed fatalities.	Occupational Non-occupational Global value (as total if the distinction is not available or clear)	Human
	C-02	Experienced annual human mortality	Average annual deaths.	Occupational Non-occupational Global value (as total if the distinction is not available or clear)	Human
	C-03	Population immediately affected	Number of immediate fatalities and/or injuries and/or evacuees in a single event.	Occupational Non-occupational Global value (all with further division into: fatalities, injured, evacuees, global value as total people affected if the distinction is not available or clear)	Human
	C-04	Trans-generational health effects	Number of human/non-human future generations at risk of adverse health effects.	Human Non-human	Human, environmental
	C-05	Experienced non-human mortality	Dead animals that have occurred.		Environmental
	C-06	Potential non-human mortality	Maximum potential dead animals.		Environmental
	C-07	Economical loss (property, rebuilding costs)	Property and rebuilding costs of the damaged facility.		Economical

	C-08	External consequences cost	External costs related to the event into analysis at different levels.	Environmental: Impact on public and occupational health, agriculture, forests, biodiversity effects, aquatic impact, impact on materials, global impact. Non-environmental: Impact on public infrastructure, security of supply, government actions.	Economical
	C-09	People affected by loss of energy supply	Number of people affected by loss/reduction of foreseen energy supply.		Human

As the indicators CT-01 and CT-02 could also be interpreted as descriptors, and not as proper indicators, the mainstay of the RCIs is what it is identified as the *core RCIs*. Thus, when speaking of RCIs, it means that the complete list is considered, while speaking about the core RCIs, it means that the list into account excludes the members related to the step choice of technology (CT-01 and CT-02).

In addition to the RCIs, five descriptors have been introduced, which add useful relevant information to complete the RCIs. They are identified, like the risk indicators, with a reference code, linked to the specific area of interest (see Table 5.2.2). The areas covered by the descriptors are two:

1. Information background – It gives information concerning the event into analysis. The event is characterised by its origin (source identification), its originating cause, and the technical location (facility) where the event started or took place. It is also specified if the event is historical or the information is coming from a predictive study.
2. Completeness of information – This thematic area wants to give the indication about how many indicators, to the total of them, are involved in the evaluation of the event. This could also be seen as a source of indirect knowledge about the quantity of information available to evaluate a specific case.

With the RCIs and their associated descriptors it is possible to reach a good level of information concerning a particular application, covering different aspects of its related risk.

Table 5.2.2: Descriptors associated to the RCIs, along with their definition and classification.

Area	Indicator identification code	Indicator	Definition	Sub-classification
Information background	IB-01	Source identification	Identification of information provider.	
	IB-02	Type of risk information	Distinction between risk information from actual events (historical) or from predictive studies.	Historical Prognostic
	IB-03	Cause	Identification of the cause of the event.	A list of various possibility should be available: Explosion, fire, release, collision, collapse, etc.
	IB-04	Technical location	Technical location where the event takes its origin.	A list of various possibility should be available: pipeline, storage tank, truck, train, ship, factory installation, power plant, etc.
Completeness of information	CI-01	Completeness	Level of completeness of the RCIs respect to the total of them.	

5.3. Evaluation of the indicators.

The incoming information is processed through the RCIs according to two types of evaluation methods:

1. Verbal-based: where the input information is expressed in the form of a verbal statement or is given as an indeterminate number (for example, a range of variation, from which a clear and unique numerical value cannot be identified). A link to a predefined evaluation list is created, with association to a specific numerical scale, which translates the initial input into a numerical value.
2. Numerical-based: where the original input information is a well-defined numerical value, mathematically processed through the numerical-based application of the RCIs.

The definition of the numerical-based RCIs scoring system relies on the example offered by (Hohenemser et al., 2000), which processes the initial value through the use of a logarithmic scale to reach the output value. Thus, the input values are converted into the logarithmic base 10 scale.

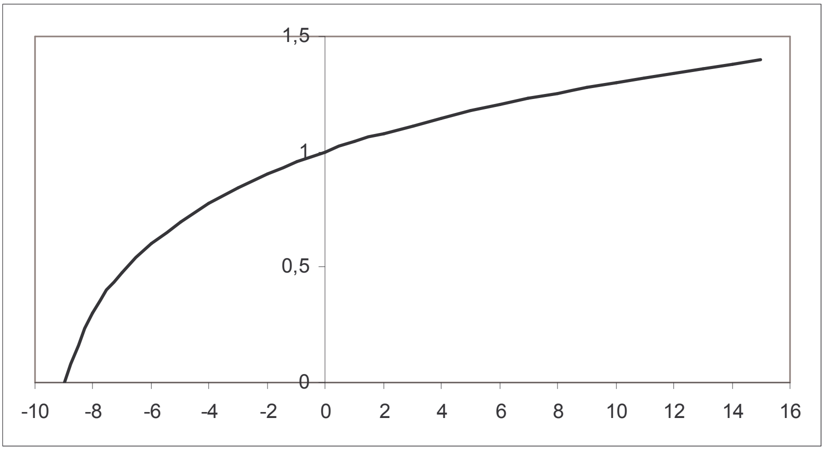


Figure 5.3.1: Function $Log_{10}(X+10)$.

The function $L = Log_{10}(X)$ presents values $L<0$ for $X<1$, and values $0\leq L<1$ for $1\leq X<10$. To avoid the inconsistencies that could be given by negative or null results in unfortunate cases when processing the numbers throughout the method, the choice is to start the scale of the logarithmic conversion from value 1, adding 10 to the logarithmic argument. Thus, each numerical-based application is going to convert the initial value according to the function $L = Log_{10}(X+10)$ (Figure 5.3.1).

5.4. Specifications and scoring system.

Every indicator and every descriptor is estimated according to a tailored evaluation system.
The RCIs listed in Table 5.2.1 are estimated to reach a numerical value as result in both the verbal-based and the numerical-based applications. Whenever it is impossible to fill a specific indicator with the required information, then the indicator becomes not relevant for the aim of the risk comparison, and can be considered NA=not applicable in the ongoing investigation.
An exception is given by the two indicators for the step 'choice of technology' (indicators CT-01 and CT-02), which are only verbally characterised.
The descriptors of the information background area in Table 5.2.2 are verbally evaluated. The case is different for the completeness descriptor, calculated on the base of the filled available RCIs.
The next sub-sections describe in details the evaluation scales for each element.

5.4.1. Indicator CT-01: intentionality.

Type of evaluation applied: verbal-based, a pre-determined text to be selected from the available list.
The list allows choosing among three different kinds of events, representing the three different categories of risk discussed in Section 1.3.2 (Chapter 1):

1. Accidental event.
2. External non-natural event.
3. Normal operation.

5.4.2. Indicator CT-02: Matrix reference.

Type of evaluation applied: verbal-based, a pre-determined text to be selected from the available list.
The choice is possible for the two different levels of specification from the matrix [A], which combines the energy systems into exam with the associated steps of the fuel/life cycle:

1. Element, identifying a step in the fuel/life cycle of a certain technology.
2. Column, identifying a complete energy chain.

5.4.3. Indicator MER-01: Concentration.

Type of evaluation applied: verbal-based and/or numerical-based.
Three different types of material/energy release are identified:

1. Release as material, including solid, liquid and gas releases.
2. Release of energy.
3. Release of nuclear radiation.

The verbal-based evaluation uses a pre-determined text to be selected from the following available choices:

- 1 = No significance = no release.
- 2 = Very low = release within accepted limits.
- 3 = Low = release slightly above accepted limits.
- 4 = Moderate = release much above accepted limits.
- 5 = High = release very much above accepted limits.
- 6 = Very high = Severe release.
- NA = not applicable, no information found.

Accepted limits for concentration are recognized to be different from country to country, and cannot be uniquely determined. However it is recognised that, in the case of historical events, the respective country regulations apply, although limits may change in time.
Every choice, with the exception of the case in which no information is found, is then translated into a numerical value, from 1 to 6.
The numerical-based evaluation starts from the three types of release concentration for material and/or energy and convert them into the chosen reference measurement system:

- Material = Gram (g).
- Energy = Joule (J).
- Nuclear radiation = GigaBecquerel (GBq).

The value X expressed in one of the listed measurement units is transformed into a logarithmic scale using the formula Log_{10} (X+10), with expected results included in a range between 1 and 10. The upper value 10 is fixed considering the Chernobyl radiation release, which is in the order of 10*E9 GBq (Vargo ed., 2000).
In case no numerical information is available, the ‘NA = not applicable, no information found’ characterisation is offered also for numerical-based evaluation and has to be selected.

5.4.4. Indicator MER-02: Persistence.

Type of evaluation applied: verbal-based and/or numerical-based.

The verbal-based evaluation uses a pre-determined text to be selected from the available list, offering the following choices:

- 1 = No significance = no persistence/event immediately finished or up to 1 hour.
- 2 = Very low = persistence ≤ 1 week.
- 3 = Low = persistence > 1 week and ≤ 3 months.
- 4 = Moderate = persistence > 3 months and ≤ 1 year.
- 5 = High = persistence > 1 year and ≤ 10 years.
- 6 = Very high = persistence > 10 years.
- NA = not applicable, no information found.

Every choice, with the exception of the case in which no information is found, is then translated into a numerical value, from 1 to 6.

The numerical-based evaluation uses *minute* as the basic measurement system to which the possible numerical values has to be reduced to. Minutes have been preferred to seconds as they have been considered more adaptable to the variety of substances and cases interesting the energy sector.

The value X expressed in minutes is converted into logarithmical scale using the formula Log_{10} (X+10), with expected results included in a range between 1 and 8. The upper value 8 is fixed considering the amount of minutes in 100 years (60*24*365 = 525600 minutes in one year, then multiplied by 100 years). 100 years have been considered as a reasonable amount of time for this indicator.

In case no numerical information is available, the 'NA = not applicable, no information found' characterisation is offered and has to be selected.

5.4.5. Indicator MER-03: Recurrence.

Type of evaluation applied: verbal-based and/or numerical-based.

The verbal-based evaluation uses a pre-determined text to be selected from the following available choices:

- 1 = No significance = no recurrence/unique event.
- 2 = Very low = recurrence > 100 years.
- 3 = Low = recurrence ≥ 10 years and < 100 years.
- 4 = Moderate = recurrence ≥ 1 year and < 10 years.
- 5 = High = recurrence ≥ 6 months and < 1 year.
- 6 = Very high = recurrence < 6 months.
- NA = not applicable, no information found.

Every choice, with the exception of the case in which no information is found, is then translated into a numerical value, from 1 to 6.

The numerical-based evaluation uses *minute*, following the example of the previous indicator, as the basic measurement system to which the possible numerical values has to be reduced to. The recurrence interval T of an event with probability P is: T = 1/P.

The value X expressed in minutes is converted into logarithmical scale using the formula Log_{10} (X+10), with expected results included in a range between 1 and 10. The upper value 10 is fixed in accordance with recent practice, as given also in (IAEA, 1998), where the screening criterion for external event is the frequency of 1*E-7 per reactor year adopted as low limit in the nuclear sector.

The frequency value into consideration, which means that for one reactor there will be an event every 10,000,000 years, and considering the amount of hours in one year (24*365 = 8760), the recurrence T, converted into logarithmical scale, give a result very close to 10 (in defect).
In case no numerical information is available, the 'NA = not applicable, no information found' characterisation is offered and has to be selected.

5.4.6. Indicator MER-04: Spatial extent.

Type of evaluation applied: verbal-based and/or numerical-based.
As far as the spatial extent is concerned, the events are mainly classified as internal and external from the interested facility area. The outcome is classified accordingly, and, if external, it is then evaluated using a pre-determined text to be selected from the available choices:

- 1 = No significance = no spatial extent.
- 2 = Very low = internal/limited.
- 3 = Low = internal/extended.
- 4 = Moderate = external/1 country.
- 5 = High = external/more countries.
- 6 = Very high = external/global.
- NA = not applicable, no information found.

Every choice, with the exception of the case in which no information is found, is then translated into a numerical value, from 1 to 6.
The numerical-based evaluation, to be considered only for cases affecting the area external to the facility, uses *meter* as the basic measurement system to which the possible numerical values has to be reduced to. If the spatial extent is given as area, this should be considered like a circle from which the radius can be calculated and considered.
The value X expressed in meters is converted into logarithmical scale using the formula Log_{10} (X+10), with expected results included in a range between 1 and 7. The upper value 7 is fixed considering a maximum spatial extent equal to the Earth circumference of 4*E7 meters.
In case no numerical information is available, the 'NA = not applicable, no information found' characterisation is offered and has to be selected.

5.4.7. Indicator MEE-01: Delay of consequences.

Type of evaluation applied: verbal-based and/or numerical-based.
Events can originate consequences, which are mainly classified as immediate and delayed. It is possible to choose among these two possibilities, and then evaluate the situation using a pre-determined text to be selected from the available list with the following choices:

- 1 = No significance = immediate/delay less or equal to 1 minute.
- 2 = Very low = delay ≤ 1 week.
- 3 = Low = delay > 1 week and ≤ 3 months.
- 4 = Moderate = delay > 3 months and ≤ 1 year.
- 5 = High = delay > 1 year and ≤ 10 years.
- 6 = Very high = delay > 10 years.
- NA = not applicable, no information found.

Every choice, with the exception of the case in which no information is found, is then translated into a numerical value, from 1 to 6.
The numerical-based evaluation, after the choice between the two sub-classification options of immediate and delayed consequences, uses *minute* as the basic measurement system to which the possible numerical values have to be reduced to. The approach is that of trying to use the same unit of measure when dealing with time in the RCIs. Thus, also in this case, minutes are preferred to seconds, as better adaptable to the large variety of cases in the energy sector.
The determined value X expressed in minutes is converted into logarithmical scale using the formula Log_{10} (X+10), with expected results included in a range between 1 and 8. The upper value 8 is fixed considering a maximum reasonable delay of consequences of 100 years (60*24*365 = 525600 minutes in one year, then multiplied by 100 years). 100 years have been considered as a reasonable amount of time for this indicator.
In case no numerical information is available, the 'NA = not applicable, no information found' characterisation is offered and has to be selected.

5.4.8. Indicator MEE-02: Population at risk (potentially affected).

Type of evaluation applied: verbal-based and/or numerical-based.
As far as the population is concerned, the classification is mainly into occupational and non-occupational, or global value if the information does not clearly distinguish between the two categories.
The people into consideration are then evaluated on a verbal basis using a pre-determined text to be selected from the second available list, offering the following choices:

- 1 = No significance = no people interested.
- 2 = Very low = individual/up to 5 people.
- 3 = Low = small group/up to 50 people.
- 4 = Moderate = large group/up to 100 people.
- 5 = High = very large group/up to 1000 people.
- 6 = Very high = country level/population of one or more countries/>1000 people.
- NA = not applicable, no information found.

Every choice, with the exception of the case in which no information is found, is then translated into a numerical value, from 1 to 6.
The numerical-based evaluation is given on the basis of the reported *number of people*. The number of people X is converted into logarithmical scale using the formula Log_{10} (X+10), with expected results included in a range between 1 and 10. The upper value 10 is fixed considering a maximum number of people equal to the Earth population, of about 6.5*E9 persons.
In case no numerical information is available, the 'NA = not applicable, no information found' characterisation is offered and has to be selected.

5.4.9. Indicator C-01: Latent fatalities.

Type of evaluation applied: verbal-based and/or numerical-based.
As far as the population is concerned, the classification is mainly into occupational and non-occupational, or global value if the information does not clearly distinguish between the two categories.

The people into consideration are then evaluated on a verbal basis using a pre-determined text to be selected from the available choices:

- 1 = No significance = no people interested.
- 2 = Very low = individual/up to 5 people.
- 3 = Low = small group/up to 50 people.
- 4 = Moderate = large group/up to 100 people.
- 5 = High = very large group/up to 1000 people.
- 6 = Very high = country level/population of one or more countries/>1000 people.
- NA = not applicable, no information found.

Every choice, with the exception of the case in which no information is found, is then translated into a numerical value, from 1 to 6.
Following the appropriate choice among occupational, non-occupational, or global value according to the first list, the numerical-based evaluation is given on the basis of the reported *number of people*.
The determined number of people X is converted into logarithmical scale using the formula Log_{10} (X+10), with expected results included in a range between 1 and 10. The upper value 10 is fixed considering a maximum number of people equal to the Earth population, of about 6.5*E9 elements.
In case no numerical information is available, the 'NA = not applicable, no information found' characterisation is offered and has to be selected.

5.4.10. Indicator C-02: Experienced annual human mortality.

Type of evaluation applied: verbal-based and/or numerical-based.
Also for this indicator, considering the number of fatalities on yearly base, a first classification allows to distinguish among occupational and non-occupational, or global value if the information does not clearly distinguish between the two categories.
The people into consideration are then evaluated on a verbal basis using a pre-determined text to be selected from the available choices:

- 1 = No significance = no people interested.
- 2 = Very low = individual/up to 5 people.
- 3 = Low = small group/up to 50 people.
- 4 = Moderate = large group/up to 100 people.
- 5 = High = very large group/up to 1000 people.
- 6 = Very high = country level/population of one or more countries/>1000 people.
- NA = not applicable, no information found.

Every choice, with the exception of the case in which no information is found, is then translated into a numerical value, from 1 to 6.
Following the appropriate choice according to the first initial classification of the interested people, the numerical-based evaluation is given on the basis of the reported *number of people*.
The determined number of people X is converted into logarithmical scale using the formula Log_{10} (X+10), with expected results included in a range between 1 and 10. The upper value 10 is fixed considering a maximum number of people equal to the Earth population, of about 6.5*E9 elements.

In case no numerical information is available, the ‘NA = not applicable, no information found’ characterisation is offered and has to be selected.

5.4.11. Indicator C-03: Population immediately affected.

Type of evaluation applied: verbal-based and/or numerical-based.
As far as the population is concerned, a first classification allows distinguishing among occupational and non-occupational people, or global value if the information does not clearly distinguish between the two categories.
The people into consideration are then evaluated on a verbal basis using a pre-determined text to be selected from the second available classification, offering the following choices:

- 1 = No significance = no people interested.
- 2 = Very low = individual/up to 5 people.
- 3 = Low = small group/up to 50 people.
- 4 = Moderate = large group/up to 100 people.
- 5 = High = very large group/up to 1000 people.
- 6 = Very high = country level/population of one or more countries/>1000 people.
- NA = not applicable, no information found.

Every choice, with the exception of the case in which no information is found, is then translated into a numerical value, from 1 to 6.
Following the appropriate choice according to the first initial sorting of the interested people, the numerical-based evaluation is given on the basis of the reported *number of people*.
The determined number of people X is converted into logarithmical scale using the formula Log_{10} (X+10), with expected results included in a range between 1 and 10. The upper value 10 is fixed considering a maximum number of people equal to the Earth population, of about 6.5*E9 elements.
In case no numerical information is available, the ‘NA = not applicable, no information found’ characterisation is offered and has to be selected.

5.4.12. Indicator C-04: Trans-generational health effects.

Type of evaluation applied: verbal-based.
The consequences of a certain event on future generations are taken into consideration for human and non-human cases, or for the both of them.
The trans-generational health effects are evaluated using a pre-determined text to be selected from the available list, offering the following choices:

- 1 = No significance = no effects.
- 2 = Very low = acceptable effects on exposed generation.
- 3 = Low = severe effects on exposed generation.
- 4 = Moderate = acceptable effects on 1 future generation.
- 5 = High = severe effects on 1 future generation.
- 6 = Very high = effects on more than 1 future generation.
- NA = not applicable, no information found.

Every choice, with the exception of the case in which no information is found, is then translated into a numerical value, from 1 to 6.

5.4.13. Indicator C-05: Experienced non-human mortality.

Type of evaluation applied: verbal-based.
The presence of fatalities in non-human beings is classified on a verbal basis using a pre-determined text to be selected from the available list with the following choices:

- 1 = No significance = no mortality.
- 2 = Very low = individual/up to 5 animals.
- 3 = Low = small group/up to 50 animals.
- 4 = Moderate = large group/up to 1000 animals/limited area.
- 5 = High = large group/up to 1000 animals/extended area.
- 6 = Very high = severe mortality/>1000 animals/ or species extinction.
- NA = not applicable, no information found.

Every choice, with the exception of the case in which no information is found, is then translated into a numerical value, from 1 to 6.

5.4.14. Indicator C-06: Potential non-human mortality.

Type of evaluation applied: verbal-based.
The potential presence of fatalities in non-human beings is classified on a verbal basis using a pre-determined text to be selected from the available list with the following choices:

- 1 = No significance = no mortality.
- 2 = Very low = individual/up to 5 animals.
- 3 = Low = small group/up to 50 animals.
- 4 = Moderate = large group/up to 1000 animals/limited area.
- 5 = High = large group/up to 1000 animals/extended area.
- 6 = Very high = severe mortality/>1000 animals/ or species extinction.
- NA = not applicable, no information found.

Every choice, with the exception of the case in which no information is found, is then translated into a numerical value, from 1 to 6.

5.4.15. Indicator C-07: Economic loss (property, rebuilding costs).

Type of evaluation applied: verbal-based.
The economic loss, limited to property and rebuilding costs (Hirschberg et al., 1998), is evaluated using a pre-determined classification based on values in US $, referred to the 2008 average value. The appropriate loss level has to be selected from the available list, offering the following choices:

- 1 = No significance = no cost.
- 2 = Very low = ≤ 500,000 $.
- 3 = Low = cost > 500,000 $ and ≤ 1,000,000 $.
- 4 = Moderate = cost > 1,000,000 $ and ≤ 10,000,000 $.
- 5 = High = cost > 10,000,000 $ and ≤ 50,000,000 $.
- 6 = Very high = > 50,000,000 $.
- NA = not applicable, no information found.

Every choice, with the exception of the case in which no information is found, is then translated into a numerical value, from 1 to 6.

5.4.16. Indicator C-08: External consequences cost.

Type of evaluation applied: verbal-based.

The consequences affecting external environmental and non-environmental economic aspects are evaluated using a pre-determined classification based on values in US $, referred to the 2008 average value. The appropriate externality level has to be selected from the available list, offering the following choices:

- 1 = No significance = no cost.
- 2 = Very low = ≤ 500,000 $.
- 3 = Low = cost > 500,000 $ and ≤ 1,000,000 $.
- 4 = Moderate = cost > 1,000,000 $ and ≤ 10,000,000 $.
- 5 = High = cost > 10,000,000 $ and ≤ 50,000,000 $.
- 6 = Very high = > 50,000,000 $.
- NA = not applicable, no information found.

The reference (Hirschberg et al., 1998) has been adopted to define the different aspects involved in the two groups of environmental and non-environmental external consequences. The distinction is the following:

Environmental: Impact on public and occupational health, agriculture, forests, biodiversity effects, aquatic impact, impact on materials, global impact.

Non-environmental: Impact on public infrastructure, security of supply, government actions.

Every listed choice, with the exception of the case in which no information is found, is then translated into a numerical value, from 1 to 6.

5.4.17. Indicator C-09: People affected by loss of energy supply.

Type of evaluation applied: verbal-based and/or numerical-based.

To define the people affected by loss of energy supply, the classification is mainly into occupational and non-occupational, or global value if the information does not clearly distinguish between the two categories.

The people into consideration are then evaluated on a verbal basis using a pre-determined text to be selected from the available list in a second choice, according to the following possibilities:

- 1 = No significance = no people interested.
- 2 = Very low = individual/up to 5 people.
- 3 = Low = small group/up to 50 people.
- 4 = Moderate = large group/up to 100 people.
- 5 = High = very large group/up to 1000 people.
- 6 = Very high = country level/population of one or more countries/>1000 people.
- NA = not applicable, no information found.

Every choice, with the exception of the case in which no information is found, is then translated into a numerical value, from 1 to 6.

Following the appropriate initial choice and distinction, the numerical-based evaluation is given on the basis of the reported *number of people*.

The determined number of people X is converted into logarithmical scale using the formula Log_{10} (X+10), with expected results included in a range between 1 and 10. The upper value

10 is fixed considering a maximum number of people equal to the Earth population, of about 6.5*E9 elements.
In case no numerical information is available, the ‘NA = not applicable, no information found’ characterisation is offered and has to be selected.

5.4.18. Descriptor IB-01: Source identification.

Type of evaluation applied: verbal, a free text can be typed by the provider of information. The text has to specify clearly the exact origin of the information.

5.4.19. Descriptor IB-02: Type of risk information.

Type of evaluation applied: verbal. The choice is from the two available types of risk information:

1. Historical.
2. Prognostic study.

5.4.20. Descriptor IB-03: Cause.

Type of evaluation applied: verbal. In case of practical implementation of the described methodology, at this stage a list of possible causes should be offered for selection.

5.4.21. Descriptor IB-04: Technical location.

Type of evaluation applied: verbal. In case of practical implementation of the described methodology, at this stage a list of possible causes should be offered for selection.

5.4.22. Descriptor VI-01: Completeness.

Type of evaluation applied: numerical, based on the number of RCIs filled with information.
The completeness value expresses the ratio between the number of indicators providing information in the specific application and the total amount of them. Each indicator is counted a number of times depending on its sub-classification.
The completeness evaluation takes into consideration only the core RCIs accounted for the maximum number of times as indicated in Table 5.4.22.1.

Table 5.4.22.1: Number of times each indicator is counted to evaluate the completeness level for verbal-based and numerical-based applications. Highlighted in gray the alternatives, to be considered when divisions are missing.

Indicator ID code	Indicator	Numerical-based application (nº.)	Verbal-based application (nº.)
MER-01	Concentration	1 (energy) 1 (material) 1(nuclear radiation)	1 (energy) 1 (material) 1(nuclear radiation)
MER-02	Persistence	1	1
MER-03	Recurrence	1	1
MER-04	Spatial extent	1 (external only)	1
MEE-01	Delay of consequences	1	1
MEE-02	Population at	1 (occupational)	1 (occupational)

	risk (potentially affected)	1 (non-occupational) or 1 (global)	1 (non-occupational) or 1 (global)
C-01	Latent fatalities	1 (occupational) 1 (non-occupational) or 1 (global)	1 (occupational) 1 (non-occupational) or 1 (global)
C-02	Experienced annual human mortality	1 (occupational-fatalities) 1 (occupational-injured) 1 (occupational-evacuees) or 1 (occupational-not spec.) and 1 (non occupational-fatalities) 1 (non occupational-injured) 1 (non occupational-evacuees) or 1 (non occupational-not spec.) or 1 (global-fatalities) 1 (global-injured) 1 (global-evacuees) or 1 (global-not spec.)	1 (occupational-fatalities) 1 (occupational-injured) 1 (occupational-evacuees) or 1 (occupational-not spec.) and 1 (non occupational-fatalities) 1 (non occupational-injured) 1 (non occupational-evacuees) or 1 (non occupational-not spec.) or 1 (global-fatalities) 1 (global-injured) 1 (global-evacuees) or 1 (global-not spec.)
C-03	Population immediately affected	1 (occupational) 1 (non-occupational) or 1 (global)	1 (occupational) 1 (non-occupational) or 1 (global)
C-04	Trans-generational health effects	-	1 (human) 1 (non-human)
C-05	Experienced non-human mortality	-	1
C-06	Potential non-human mortality	-	1
C-07	Economical loss (property, rebuilding costs)	-	1
C-08	External consequences cost	-	1 (environmental) 1 (non-environmental)
C-09	People affected by loss of energy supply	1 (occupational) 1 (non-occupational) or 1 (global)	1 (occupational) 1 (non-occupational) or 1 (global)
TOTAL (excluding alternatives)		**21**	**28**

Thus, the total possible core RCIs for both numerical-based and verbal-based applications to be considered in the ratio to calculate the completeness are 49, having available distinctions for interested cases. Otherwise, alternatives, such as global values and not specified solutions, must be considered and the total number of indicators in the ratio should be changed accordingly.

5.5. Use of the indicators: possible applicability and specificity of the core RCIs.

As previously discussed when the set has been introduced, the RCIs comprises a group of primary interest: the core RCIs. In this section the core RCIs are evaluated according to two criteria:

1. The specificity, that is the different level of applicability of the indicators into analysis to the proposed list of energy systems.
2. The applicability, or possibility to find data, that is the identification of the possible level of available resources for the different energy systems into analysis.

The specificity of the core RCIs is shown is Table 5.5.1. The table accounts for different degrees of specificity based on a three-level scale, dividing the indicators into general, limited, and specific, in relation to their applicability to the different indicated energy systems.

Indicators identified as ‘general’ can be applied to a large number of energy systems, while those with ‘limited’ or ‘specific’ applicability describe mainly the characteristics of specific energy chains.

Most of the core RCIs listed in Table 5.5.1 have an extensive applicability and fall in the category general. Two indicators are classified as limited (experienced non-human mortality, and potential non-human mortality) and two as specific (latent fatalities, and trans-generational health effects). These two specific indicators have been developed to pay particular attention to radiological effects arising from radioactive releases, possible in the nuclear chain and, in minor but not negligible part, in the coal chain (Gabbard, 1993) (World Nuclear Association, 2004).

The results of the analysis across the specificity of the core RCIs is partially reflected in Table 5.5.2, which shows an evaluation of the possibly available resources in case of application. The large assortment in information sources needs to be considered when collecting data. When identifying the probability to access information for every single indicator, it is necessary to consider not only incident/accident databases, but also other available reported risk information, and risk assessments. In some cases the data to evaluate the indicators can be directly available in the correct form and measurement system, but in other cases they must be extracted from the original source and elaborated to fit into the methodology.

Looking at Table 5.5.2, it is possible to immediately recognize that conventional energy sources present the higher availability of resources. This is due to the fact that these technologies have already been in use for decades, mainly in the form of centralized energy production. Incidents and accidents have been collected since long time ago, and available historical data, as well as risk studies, are easily accessible.

Renewable energy technologies, with the exception of hydropower, have experienced an extraordinary growth in recent years, while in the past their use was very limited. Renewable technologies in some cases are quite new, still in development to be competitive in the energy market, and their applications are mainly in the form of distributed generation, with installations of limited power. Renewable energies are often considered as complementary to conventional energy sources. Their use is still quite limited compared with fossil fuels or nuclear (with the exception of hydro power, which has world shares of electricity production comparable to nuclear (IEA, 2007)). This is directly translated into minor information and a limited number of significant risk events, which is subsequently translated into difficulties in finding information, as the case, for example, of solar energy and wind energy.

Like renewable energy systems, hydrogen exhibits a similar problem, being a new technology approaching the energy market. Hydrogen had a very limited use in its historical background as energy carrier, and this is translated into risk information very difficult to find and collect.

Finally, when an indicator is not considered to be of interest for a specific energy system, which corresponds to an empty cell in Table 5.5.1, then it is associated to the improbability to find data and/or information as indicated in Table 5.5.2.

One could criticize the inclusion of hydrogen, as an energy carrier, in a comparison between energy fuels. The author has taken the decision to list hydrogen among the other energy chains, with the knowledge that the level of hazard relies also on the consideration of its production pathway. The decision has been taken considering that hydrogen is burned, in the end, to produce useful energy as any other fuel (such as gas or oil), and additionally looking at the scope of the methodology in development. The RCIs have been developed with the idea in mind that the finalised tool should not consider the risk of the energy source by itself, but has to evaluate the technologies adopted in processing a certain fuel, according to its fuel cycle. From this point of view, hydrogen technologies are not an exception and should be included as well, as they are considered relevant for the future of electricity production. It will be then up to the users to make other consideration about the production pathways of hydrogen, which can influence its final level of risk impact.

The indications shown in Table 5.5.1 and Table 5.5.2 are not intended to provide a concluding evaluation of the core RCIs, but they only want to give suggestions concerning their specificity and applicability. They propose the judgment of the author, elaborated with the support of the expertise of relevant researchers in the energy fuel/life cycle assessment area.

Table 5.5.1: The table shows the specificity of the core RCIs to characterize events in the related energy chains. The table has been filled consulting the judgment of some researchers in the energy fuel/life cycle assessment area.

	Spatial extent	Concentration	Persistence	Recurrence	Delay of consequence	Population at risk (potentially affected)	Population immediately affected	Experienced annula human mortality	Latent fatalities	Transgenerational health effects	Experienced non-human mortality	Potential non-human mortality	Economic loss (property and rebuilding costs)	External consequences cost	People affected by loss of energy supply
Coal	G	G	G	G	G	G	G	G	S	S	L	L	G	G	G
Oil	G	G	G	G	G	G	G	G			L	L	G	G	G
Natural gas	G	G	G	G	G	G	G	G					G	G	G
Nuclear	G	G	G	G	G	G	G	G	S	S	L	L	G	G	G
Biomass	G	G	G	G	G	G	G	G					G	G	G
Geothermal	G	G	G	G	G	G	G	G					G	G	G
Hydro	G		G	G		G	G	G			L	L	G	G	G
Solar	G	G	G	G	G	G	G	G					G	G	G
Wind	G	G	G	G	G	G	G	G			L	L	G	G	G
Hydrogen	G	G	G	G		G	G	G					G	G	G

Legend:

G	General	For more than 6 energy chains among those considered
L	Limited	From 4 to 6 energy chains
S	Specific	From 1 to 3 energy chains

Table 5.5.2: Probability to find data or information for each core RCIs in relation to every involved energy chain. The table has been filled consulting the expertise of some researchers in the energy fuel/life cycle assessment area.

	Spatial extent	Concentration	Persistence	Recurrence	Delay of consequence	Population at risk (potentially affected)	Population immediately affected	Experienced annula human mortality	Latent fatalities	Transgenerational health effects	Experienced non-human mortality	Potential non-human mortality	Economic loss (property and rebuilding costs)	External consequences cost	People affected by loss of energy supply
Coal	M	M	M	M	M	H	H	H	M	H	M	M	H	H	M
Oil	M	M	M	M	M	H	H	H	I	I	M	M	H	H	M
Natural gas	M	M	M	M	M	H	H	H	I	I	I	I	H	H	M
Nuclear	H	H	H	H	H	H	H	H	H	H	M	M	H	H	M
Biomass	D	D	D	D	D	M	D	M	I	I	I	I	M	M	D
Geothermal	D	D	D	D	D	D	D	D	I	I	I	I	D	D	D
Hydro	H	I	D	M	I	H	H	H	I	I	M	D	H	H	M
Solar	M	H	M	D	D	D	D	M	I	I	I	I	M	M	D
Wind	D	D	D	D	D	M	M	M	I	I	M	M	M	M	D
Hydrogen	M	D	D	D	I	D	M	D	I	I	I	I	D	D	D

Legend:

H	High
M	Medium
D	Difficult
I	Improbable

5.6. Composition with probability.

In view of obtaining the risk evaluation necessary for the methodology under discussion along this thesis, it is necessary to combine the first outcome of the core RCIs with the related probability value. Probability data on specific cases could be difficult to collect and sometimes they could represent confidential information not accessible for an independent scientific evaluation. Imposing this assumption, and introducing also the additional assumption to have this methodology applied as a tool relying on a supporting database containing an acceptable amount of information, the way to obtain the necessary probability is discussed further in this section.

The situation is actually that of a person who needs to choose under uncertainty, thus having a feeling of incomplete information, and having the need to rely on his/her own rationality.

Each estimate of probability is conditional to the information currently available when making evaluations, it involves a personal degree of belief characterised by the personal uncertainty in the evaluation (Bernardo & Smith, 1994).

As stated by Jaynes, probability distributions are carriers of incomplete information. This means also that they indirectly express the uncertainty that a person has about that event and that evaluation. The value of a probability is always closely connected to the level of information available for the evaluation. Further information can change the perception of the uncertainty in which a person can find himself/herself when making decisions, and this can change probabilities, making events more, or less plausible.

It is clear at this point that all probabilities are conditional at least on all the knowledge a person has until the moment he/she is entitled to make decisions. Let's call X this amount of past experience. All the probabilities conditional to X alone are called prior probabilities.

In the context of this thesis it is considered to have a given a set of observations and a certain prior knowledge to evaluate the probability assignment. This is translated in the elements X, H, and D, whose meaning is clarified in Table 5.6.1.

Passing through Jaynes' discussion on prior probabilities (Jaynes, 2003), the Bayes' theorem is used for the purpose of this application.

Table 5.6.1: Notation used in the formulas as stated in (Jaynes, 2003) and as requested by the context of this thesis.

Notation	Meaning according to (Jaynes, 2003)	Meaning in the context of the RCIs
X	Prior information.	Prior knowledge on energy systems.
H	Some hypothesis to be tested.	Assignment to probability value and/or choosing the rules (distribution functions) for event probabilities.
D	The data.	Data in the database (if one), about a specific case.

Accepting that X is given and it is true, the plausibility of H and D are evaluated following the paths shown in Figure 5.6.1. From the scheme it appears that the probability change according to the new information gained and depends on that.

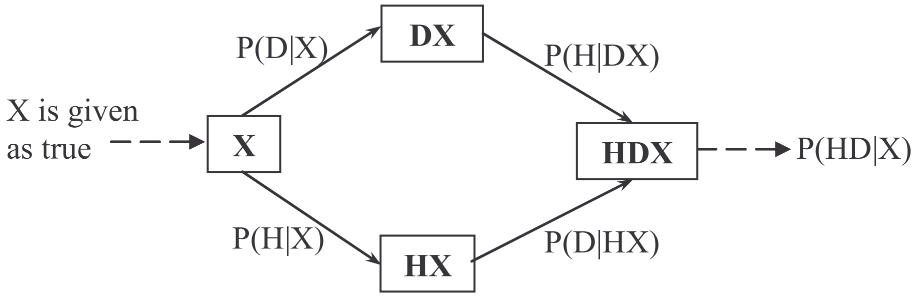


Figure 5.6.1: Paths to support the product rule and verify the plausibility of D and H, given our prior knowledge X.

The paths in Figure 5.6.1 describe what is written in the product rule (Jaynes, 2003):

$$P(HD|X) = P(D|HX) \cdot P(H|X) = P(H|DX) \cdot P(D|X) \tag{5.1}$$

From the second equality of (5.1), it is possible to extract the following formula:

$$P(H|DX) = P(H|X) \cdot \frac{P(D|HX)}{P(D|X)} \tag{5.2}$$

The formula (5.2) gives what is called Bayes' theorem, which actually represents the process of learning from experience. Remembering the notation in Table 5.6.1, we can judge the truth of our hypothesis H in light of the available data.
The terms in (5.2) stand respectively for:

$P(H|DX)$= posterior probability.

$P(H|X)$= prior probability.

$P(D|HX)$= likelihood.

$P(D|X)$= predictive probability.

Prior and posterior are terms with a cause-effect connotation. They have the meaning of logically first or later in the chain of inference being done. Nevertheless, the distinction among the listed members of (5.2) is not fundamental, but it is only conventional. There is just one kind of probability, and the way we call it only refers to the way we organize the calculation (Jaynes, 2003).
From expression (5.2) it clearly appears that our prior knowledge X affects all terms. The same equation could be simplified and written as:

$$P(H|D) = P(H) \cdot \frac{P(D|H)}{P(D)} \tag{5.3}$$

This represents a more common expression of Bayes theorem (Bernardo & Smith, 1994).
It is not the case to enter in mathematical details and explanations in this context, but it is important to have clear in mind the meaning of this theorem and the way to use it.

To give an example of application, let's consider that it is necessary to determine the probability of having 15 occupational fatalities in case there is a pipeline explosion, to combine with the outcome of indicator C-03 (population immediately affected).
In the available database there are 2000 cases of pipeline explosion, of which 10 have a number of occupational fatalities equal to 15. So, P(H) = 10/2000 = 0,005.
Let D be the event of having a pipeline explosion. P(D|H) = 0,07 meaning that 7% of the times there are 15 occupational fatalities the event is associated to a pipeline explosion.
P(D|nonH) = 0,5 meaning that 50 cases in 100 are events of pipeline explosion with a different number of occupational fatalities.
The answer to the proposed problem is:

$$P(H|D) = P(H) \cdot \frac{P(D|H)}{P(D)} = P(H) \cdot \frac{P(D|H)}{P(D|H)P(H) + P(D|nonH)P(nonH)} =$$

$$= 0{,}005 \cdot \frac{0{,}07}{0{,}07 \cdot 0{,}005 + 0{,}5 \cdot (1 - 0{,}005)} = 7E^{-4}$$

The values that we need to consider in such applications are the median of the distributions associated to each probability, according to the respective specific evaluation formula.
In this section a path to evaluate probabilities has been proposed. Anyhow, this is only a methodological discussion, and the method itself is not yet translated into a tool. As long as a reasonable supporting database is not available, it becomes difficult to wholly apply what discussed.
This brings to the introduction of specific assumptions for particular probability evaluations in the case of limited applications. For example, this is the case of the application discussed in (Colli et al., 2008b), which is based only on few accidental events involving fossil fuel chains. In that case, it was not possible to rely on a supporting database, and specific assumptions had to be made. The text of this article is available in Part IV, Chapter II, publication III.

5.7. References.

(Bernardo & Smith, 1994) – J.M. Bernardo, A.F.M. Smith, "Bayesian Theory", Wiley series in probability and statistics, ISBN-10: 0-471-92416-4, March 1994.

(Colli et al., 2008a) - A. Colli, A.L. Vetere Arellano, C. Kirchsteiger, B.J.M. Ale, "Risk characterisation indicators for risk comparison in the energy sector", Safety Science, 47 (1), pp. 59-77, Elsevier, Jan 2009, http://dx.doi.org/10.1016/j.ssci.2008.01.005

(Colli et al., 2008b) - A. Colli, D. Serbanescu, B.J.M. Ale, “Indicators to Compare Risk Expressions, Grouping, and Relative Ranking of Risk for Energy Systems: Application with Some Accidental Events from Fossil Fuels”, Safety Science, 47 (5), pp. 591-607, Elsevier, May 2009, http://dx.doi.org/10.1016/j.ssci.2008.07.022

(Gabbard, 1993) – A. Gabbard, “Coal Combustion: nuclear resource or danger”, ORNL Review 26, 3-4, 1993, http://www.ornl.gov/info/ornlreview/rev26-34/text/colmain.html

(Hirschberg et al., 1998) - S. Hirschberg, G. Spiekerman, R. Dones, "Project GaBE: Comprehensive Assessment of Energy Systems. Severe Accidents in the Energy Sector", First edition, Paul Scherrer Institut, ISSN-1019-0643, 1998.

(Hohenemser et al., 2000) - C. Hohenemser, R.W. Kates, P. Slovic, “The Nature of Technological Hazards”, chapter 10 from the book: “The perception of Risk. Risk, Society and Policy”, P. Slovic editor, Earthscan, (2000).
(IAEA, 1998) - INSAG, Basic Safety Principles for Nuclear Power Plants, Safety Series No.75-INSAG-3, IAEA, Vienna, 1998.
(IEA, 2007) – International Energy Agency, "Key World Energy Statistics", 2007.
(Jaynes, 2003) - E.T. Jaynes, "Probability Theory: The Logic of Science", edited by G. Larry Bretthorst, ISBN-13: 9780521592710, ISBN-10: 0521592712, DOI: 10.2277/0521592712, published April 2003.
(Vargo ed., 2000) - G.J. Vargo ed., “The Chernobyl Accident. A Comprehensive Risk Assessment”, Battelle Press, Ohio, 2000.
(World Nuclear Association, 2004) – World Nuclear Association, “Naturally-Occurring Radioactive Materials (NORM)”, August 2004, http://www.world-nuclear.org/info/printable_information_papers/inf30print.htm

6. The grouping and ranking methodology.

6.1. Scope of grouping and ranking.

The purpose of the methodology proposed in this thesis is to allow risks comparison from different energy systems. With the indicators as they have been presented in the previous Chapter 5, without grouping them, it is only possible to process a comparison based on the value of each single indicator, comparing only similar indicators. They represent different aspects of energy risks and each indicator is evaluated on a tailored scale. With data and information processing through the RCIs the result is a set of tuned values, meaning that different scales and different interpretations of risk expressions are uniformed. For a demonstration see the paper "Risk characterisation indicators for risk comparison in the energy sector" in Part IV, Chapter II, publication II. But this is not the only scope of developing such a comparative methodology.

The purpose of this work is also that of investigating the possibility to group the indicators, combining them to reach an overall value giving information on the risk level of the case under analysis. Achieving the goal of having an overall risk value can be useful, for example, when the aim is to convert various risks into a geographical representation, identifying iso-risk curves and areas.

The purpose of reaching an overall risk value needs the investigation of possible methodologies taking into account the weight of each indicator as well as being able to overcome the substantial differences in the significance of each RCI. These issues are going to be discussed in the next sections, where existing grouping and ranking methodologies are evaluated and a new approach is presented.

6.2. Methodologies in use.

When there is the need to evaluate different choices (risk events) on the base of various criteria (the RCIs) the connection with multi criteria decision analysis (MCDA) methodologies is immediate. There is a large number of methods to be listed under the MCDA category, some more and some less famous, but with the similar aim to guiding the decision-maker in taking complicated decisions, highlighting the best (or the worse, it depends on the situation) option among those available.

One of the most well known MCDA methods is the Analytical Hierarchy Process (AHP), a decision making mathematical procedure developed by Thomas Saaty (Saaty, 1980).

The AHP provides an effective means to deal with complex decision making problems and allows a better, easier, and more efficient identification of selection criteria, their weighting and their combination. The method involves building a hierarchy (ranking) of decision elements and then making comparisons between each possible pair in each group. This gives a weighting for each element within a level of the hierarchy. The matrix of weight ratios is thus built. Saaty proposed to approximate this matrix of weight ratios with another matrix [A], called the pair-wise comparison matrix, whose elements are based on an integer-valued 1-to-9 scale.

If the AHP was chosen for use with the RCIs, it is possible, in the optimal case when all core RCIs are quantified, to reach a high number of elements in the pairwise comparison matrix. It is necessary then to warn the user about an optimal limit of 7±2 elements to compare. According to (Miller, 1956) “the span of absolute judgment and the span of immediate memory impose severe limitations on the amount of information that we are able to receive, process, and remember”. In this way Miller hypothesizes 7±2 elements as a limit for reliable results when processing information on simultaneously interacting elements.
Later, in (Saaty and Ozdemir, 2003), it is demonstrated that this limit applies also to the number of elements of a group, whose pairs are judged according to the AHP.
The reason of this limit in AHP can be found in the consistency checking of the pairwise comparison matrix. Practically, this means that increasing the number of elements in the pairwise comparison matrix, the correspondent increase in inconsistency is too small to identify the cause and correct the relations among different elements of comparison simultaneously. Our mind is considered sensitive enough to improve large inconsistencies, but not the small ones. Thus the number 7±2 is fixed as a barrier to obtain reliable results in judgment.
This consideration about the limited number of element in the comparison group should be taken into account. If considering the application, when the amount of indicators to be compared exceed the maximum number of 9 (7+2), it is then necessary to divide them in different groups, and proceed to a comparison by steps.
As the AHP involves directly the user and is based on his personal judgment, the definition of the possible groups will be left to the user himself/herself, who can choose to divide indicators according to different criteria (economic, environmental, etc) related to his interest.
From this first approach to the AHP methodology, in addition to the limitation in the number of criteria, the involvement of the subjective evaluation of the decision maker appears clearly. Although it is typical from the MCDA methods to involve directly the decision maker in the ranking process, allowing him/her to express opinions through the definition of weights, the instability of the human judgment should be possibly avoided in the context of energy risks comparison. Human perceptions and judgments are subject to variation when the knowledge or the psychological status of the decision maker changes. A fixed-in-time weighting factor is difficult to allocate.
This discussion can be extended and can find many connections to psychological studies. Anyhow, in this context, the purpose is only that of highlighting the variability that can be associated to a certain judgment or to a certain decision being made.
When making decisions, humans follow a certain path, as illustrated in Figure 6.2.1. As explained by Tart (Tart, 2000), this involves intellectual and cognitive processes, conscious evaluation, but also emotions and subconscious can intervene in the course of action. If only the conscious and intellectual kind of decision making and evaluation process are considered, this involve the application of logic and processing available data according to that logic. Despite this limitation, "*note that a logic is a self-contained, arbitrary system*" (Tart, 2000) and "*much of what passes as rationality…is in fact rationalization. We want something, so we make up good reasons for having it*", which means that even using logic in reasoning, we introduce a great part of subjectivity and personal point of views.
It would also be interesting to validate these observations introducing philosophical concepts associated to the presence of many egos continuously affecting the identity and the decisions of a person, but this further investigation is left to the reader (see, for

example, (Ouspensky, 1949) written in the form of a personal account of Ouspensky's years with George Gurdjieff, a Greek-Armenian philosopher and spiritual teacher).

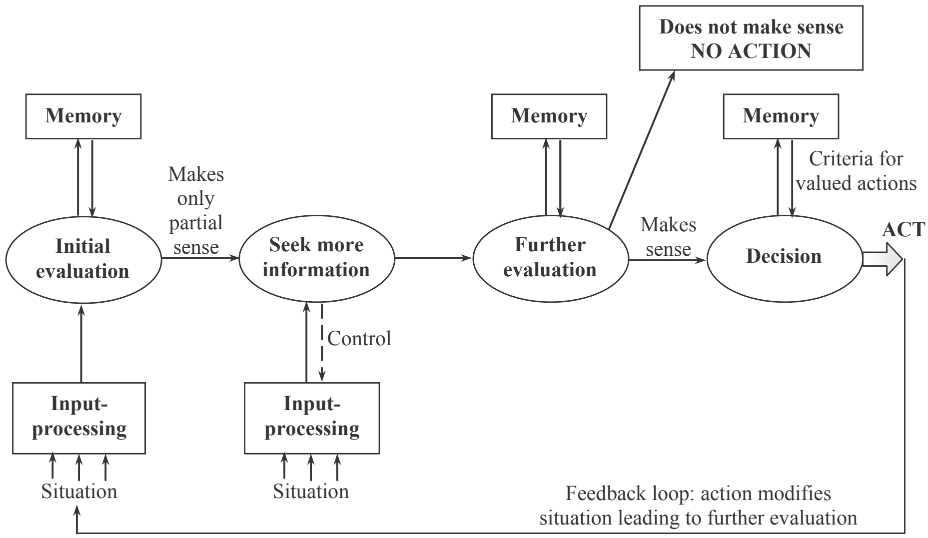


Figure 6.2.1: Steps in a typical evaluation and decision-making process (Tart, 2000).

The continuous change in a person's judgment according to his/her present state could create problems in particular contexts like that of comparison of energy risks. In fact, the use of MCDA could lead to excessive subjectivity in the energy risks comparison process and its use has also been criticized by reviewers.
In fact, the MCDA methods introduce a high degree of subjectivity into the grouping and ranking procedure, as they always involve the judgment of the decision maker to define the weighting factors associated to the various criteria (here the indicators) under investigation.
This has pushed the author to look for possible alternatives. An optimal solution has been found in adapting to this circumstance the approach based on Probabilistic Safety Assessment (PSA), proposing a new use of such a method in risk management. Details regarding this method and its development and use with the RCIs are discussed in the next sections of this chapter.
For indicative considerations, Table 6.2.1 offers an overview of the principal elements, the strengths, and the weaknesses of the PSA-based Boolean combination method and some other MCDA processes.

Table 6.2.1: Main elements, strengths, and weaknesses of the PSA-based Boolean combination method and few other MCDA methodologies. Due to the elevate number of MCDA methods, the table only wants to be indicative and considers some of the most common MCDA models.

Method	Principal elements	Strengths	Weaknesses
Boolean Combination Method	The interdependencies among criteria are converted in Boolean logic form. The weights are evaluated	Weights are not determined by a scale and do not involve the decision maker in choice, substantially	Limitations given by the simulation program. Ranking of choices is relative, and not absolute.

	using the Fussell-Vesely formula and processed with the Shannon approach to obtain ranking.	decreasing subjectivity.	
Analytical Hierarchy Process (AHP)	Decomposes complex problems into a system of hierarchies. The decision maker has to express opinion on a single pairwise comparison at a time (Triantaphyllou, 2002). Similar to MAUT, it completely aggregates various facets of the decision problem into a single objective function. The selected alternative has the greatest value (Linkov et al., 2004).	It uses relative values instead of actual ones, thus is valid for single or multidimensional decision making problems (Triantaphyllou, 2002). The method can easily proceed even when the judgemental statements are incomplete (Lootsma, 1999). Surveying pairwise comparisons is easy to implement (Linkov et al., 2006).	Ranking events through the use of the AHP need to limit the number of elements in one comparison (events and/or indicators) to 7 ± 2 (Saaty and Ozdemir, 2003). The weights obtained by pairwise comparison are criticized for not reflecting people's true preferences. The mathematical procedures can give illogical results; for example, rankings are sometimes not transitive (Linkov et al., 2006).
Simple Multi-Attribut Rating Technique (SMART)	The method evaluates a finite number of alternatives under a finite number of criteria. The alternatives are ranked in subjective order of preference. Having alternatives, criteria, and weights, the judgment of the overall performance of alternatives under all criteria simultaneously follows the arithmetic mean aggregation rule. Decision maker may ignore the units of performance measurements because the grades do not depend on them. The relative importance (weight ratio) of the criteria is considered a meaningful concept in this method even in isolation from immediate context (Lootsma, 1999).	The method can handle qualitative and quantitative criteria (Lootsma, 1999). Simplified MAUT/MAVT methods (as SMART) are robust and replicate decisions made from more complex MAUT/MAVT analysis with high degree of confidence (Linkov et al., 2004).	It allows for use of less of the scale range if the data do not discriminate adequately so that alternatives, which are not so different for a particular criterion, can be scored equally (Linkov et al., 2004).

Multi Attribute Utility/Value Theory (MAUT/MAVT (o MAVF))	Using utility/value functions the method transforms diverse criteria into one common dimensionless scale. For assumption, the decision maker is rational (more preferred to less, preferences do not change, decision maker has perfect knowledge, preferences are transitive) (Linkov et al., 2004). Based on utilitarian philosophy. Criteria weights are often obtained by directly surveying stakeholders (Linkov et al., 2006).	The method leads to a complete ranking of all alternatives based on decision maker's preferences (Linkov et al., 2004). Easier to compare alternatives whose overall scores are expressed as single numbers. Choice of an alternative can be transparent if highest scoring alternative is chosen (Linkov et al., 2006).	Concerns on practical implementability of the method, which actually led to the development of SMART (Linkov et al., 2004). Maximization of utility may not be important to the decision maker. Criteria weights obtained through less rigorous surveys may not accurately reflect true preferences. Rigorous stakeholder preference elicitations are expensive (Linkov et al., 2006).
Elimination and Choice Translating Reality (ELECTRE). Other available outranking methods: PROMETHEE, Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), VIKOR, REGIME analysis.	Criteria with dimensions are converted into non-dimensional criteria. Pairwise comparisons among alternatives, defining threshold levels of differences. It results in binary relations of alternatives, which can be complete or incomplete. Results in relative importance (Triantaphyllou, 2002). Outranking considers the dominance of one alternative over another. Comparison is in pairs (Linkov et al., 2004). In the case of TOPSIS, alternatives should have the shortest distance (in Euclidean approach) from the ideal solution, and the farthest from the negative-ideal. The ideal is determined thinking that each criterion can monotonically increase or decrease utility (Triantaphyllou, 2002).	Strenght of outranking methods, in comparison with MAUT and AHP, is the ease with which semi- or non-quantitative approach can be handled. In outranking approaches multiple points of view can be represented by representing different stakeholders with different intercriteria weightings. Outranking methods are more flexible than MAUT or AHP and they allow stakeholders to change their minds by adjusting weightings or introducing new criteria at any time during the analysis (Linkov et al., 2004). Does not require the reduction of all criteria to a single unit (Linkov et al., 2006).	The outranking methods are used where the criteria are not all considered commensurable, and therefore no global score can be produced. Weights are defined by the decision maker. The result is a definition of a core of leading alternatives, but the most preferred alternative is sometime not recognized as binary relations can be incomplete. Limited acceptance by scientific and practitioners communities (Triantaphyllou, 2002). Criteria limit to 13 (Figueira et al., 2005). Outranking methods allow for intransitivities in criteria weightings and for alternatives that are not considered comparable. Thus the order of alternatives can be incomplete (Linkov et al., 2004).

			Does not consider if the overperformance of one criterion can compensate the underperformance of another. Algorithms of outranking methods are complex and not easy to understand by decision makers (Linkov et al., 2006).
Weighted sum model (WSM)	If the criteria are preferentially independent of each other and if uncertainty is not formally built into the model, then the method is applicable (Communities and Local Governments UK, 2000).		Problems in multi-dimensional problems, where the additive utility assumption is violated (Triantaphyllou, 2002).

6.3. A possible alternative: the PSA-based Boolean logic-related methodology.

The idea of using the PSA-based approach to relatively rank risk events is based on the mathematical meaning of a PSA study.

The PSA model defines a σ-algebra on the set of all possible failure combinations leading to an altered 'risky' state of the model.

A σ-algebra is a mathematical concept denoting a collection of subsets of a given set; it is a notion necessary for the definition of measure.

Let X be a set. Then, a σ-algebra F is a nonempty collection of subsets of X such that the following hold (Wolfram MathWorld):

1. X is in F.
2. If A is in F, then so is the complement of A.
3. If A_n is a sequence of elements of F, then the union of the A_ns is in F.

For this σ-algebra a norm can be defined, which is called "risk" and which is a measure (a function that assigns a number to a set), giving the distance among the considered elements of the σ-algebra. These elements consist of end states of various scenarios assumed in a PSA-like modelling (Serbanescu, 2005a).

In general, the PSA approach groups various tasks, as shown in Figure 6.3.1. Starting from design modelling (DM), then the system analysis is performed identifying basic events (E) and initiating events (IE); following the order, the next task is the event sequence analysis, conducted on the base of fault trees (FTS) and event trees (ETS). The final tasks of the procedure include the evaluation of the consequences (CSQ) and, finally, the quantification of risk.

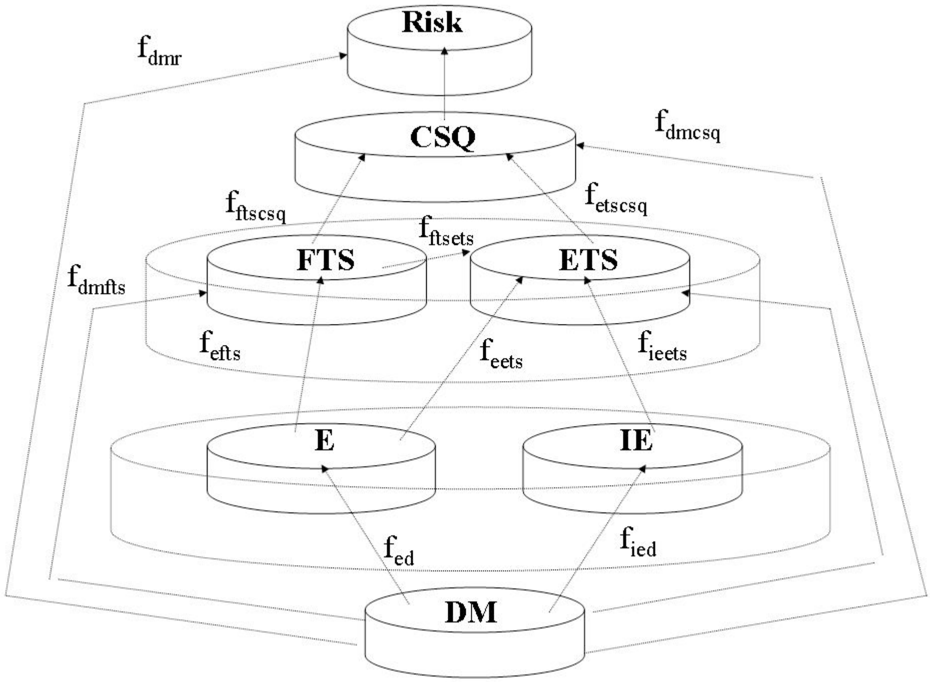


Figure 6.3.1: Typical PSA tasks as defined in (Serbanescu, 2005b).

A more detailed look, as example, into the task of event sequence analysis is shown in Figure 6.3.2.

A certain sequence from a specific event tree is represented by an element (es_n) from the event sequences set. This evaluation is defined based on the design (d_n), the initiating events (ie_n), the basic events (e_n), and the minimal cutsets (MCS) evaluated from fault tree analysis (fts_n).

For a given phase of PSA (DM, IE, E, ETS, FTS, CSQ, and Risk) a σ-algebra is defined for all the combinations of sets obtained by union (U) or intersection (∩) of elements indicating failure states.

For a certain σ-algebra a number (probability) is associated to each element. Using "+" and "·" operations with Boolean meaning, a vector space can be defined (Serbanescu, 2005b). The definition of vector space and its property can be found, for example, in (Wolfram MathWorld). For this vector space, we define risk (as combination of damage and probability) as a norm, giving a measure.

Using the concept of measure and having a set of risk events to compare, the PSA-based ranking method defines the distance of each event from the most dangerous in relative terms. The concept of distance from a certain solution (normally the optimal one), mostly expressed in the form of pairwise comparisons, can also be found in MCDA methods. This creates already a link between the PSA-based Boolean ranking approach and the area of MCDA.

The benefits of this method in comparison with other MCDA methodologies have been mentioned in Table 6.2.1, but will become clearer in the next sections when the details are explained.

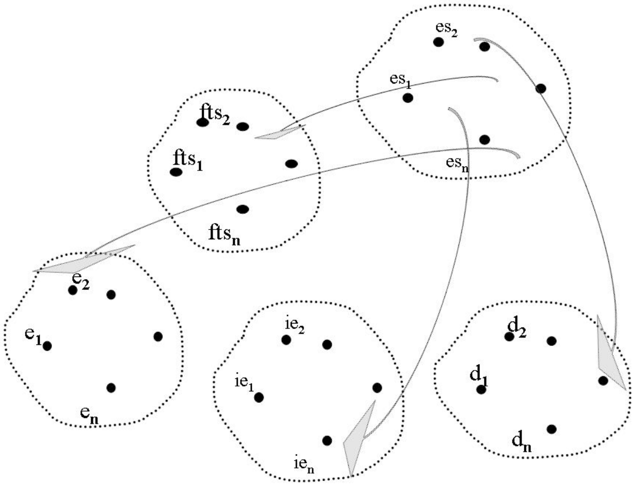


Figure 6.3.2: Functions used to build the event sequence analysis set in PSA as described in (Serbanescu, 2005b).

The passage from the causal chain for hazards development in the energy sector and the associated characterization indicators to the PSA structure including event and fault trees is indicatively shown in Figure 6.3.3. Using a little creativity, the structure of the causal chain itself already recalls an event tree (ET), while the indicators associated to each single step are connected through the use of the fault tree (FT) approach, where the logic gates OR and AND express respectively the independencies and the dependencies of the indicators.
The steps of the causal chain are converted into the function events in the top part of the event tree, adding, for modelling purposes, the input event as the initiating event. Each event is connected to a fault tree.

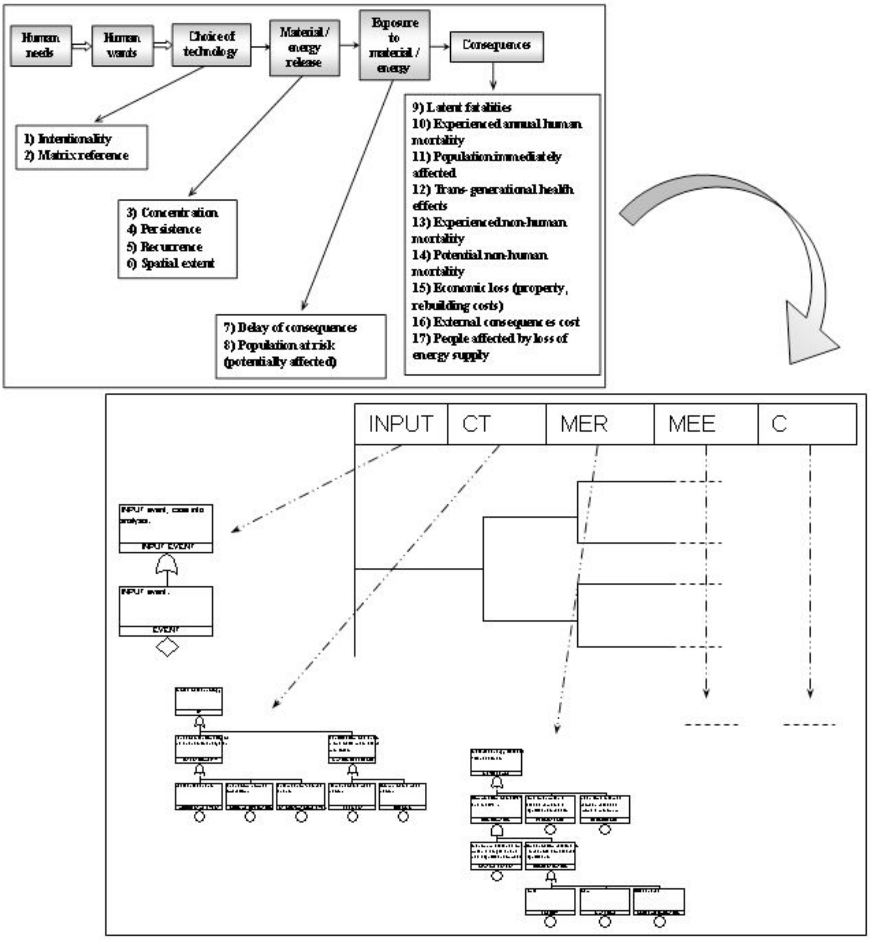


Figure 6.3.3: The causal chain is converted into an event tree, where the initiating event and the function events are connected to specific fault trees built with the indicators respectively associated to each step.

6.4. Modelling.

The development of the PSA model for the indicators basically follows the common rules for event trees and fault trees construction, as explained, for example, in (Kumamoto & Henley, 1996) and in (Bedford & Cooke, 2001).

To build the PSA-type model for the RCIs, the first step is to state the interdependencies of the indicators, for each single step of the supporting causal chain.

During this procedure, the reference for the codes of the indicators and their links to the causal chain is Table 5.2.1.

The dependencies and independencies of the indicators are set as follows:

- Choice of technology:

- o Indicators CT-01 (intentionality) and CT-02 (matrix reference) are assumed as independent.
- Material/energy release:
    - o Indicators MER-01 (concentration) and MER-04 (spatial extent) are assumed as dependent.
    - o Indicators MER-02 (persistence) and MER-03 (recurrence) are assumed as independent.
- Exposure to material/energy:
    - o Indicators MEE-01 (delay of consequences) and MEE-02 (population at risk) are assumed as independent.
- Consequences:
    - o The indicators are assumed dependent/independent according to the paths shown in Figure 6.4.1.

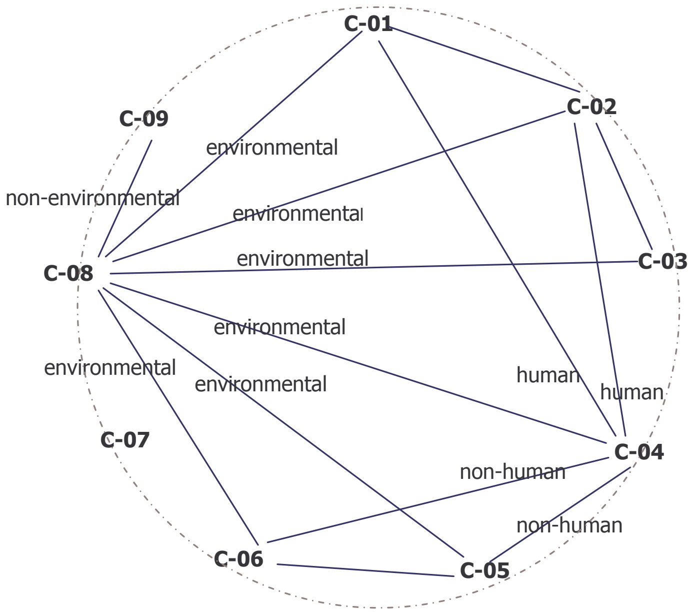


Figure 6.4.1: Diagram showing the possible links among the indicators of the consequences step in the causal chain (Colli et al., 2008). These links are translated into possible sets of combinations, useful for the transfer into the fault-tree-like model. The indicators are represented with their identification codes, according to the list in Table 5.2.1.

A deeper discussion is needed concerning the interdependencies of the consequences step and the associated indicators. As shown in Figure 6.4.1 the only indicator assumed independent is C-07 (economical loss).
The other indicators are assumed dependent as follows:

- From the perspective of C-01 (latent fatalities) the dependency group is: C-01, C-02, C-04 (human), C-08 (environmental).
- From the perspective of C-02 (experienced annual human mortality) the dependency group is: C-01, C-02, C-03, C-04 (human), C-08 (environmental).

- From the perspective of C-03 (population immediately affected) the dependency group is: C-02, C-03, C-08 (environmental).
- From the perspective of C-04 (trans-generational health effects) the dependency group is: C-01, C-02, C-04 (human and non-human), C-05, C-06, C-08 (environmental). These dependencies can be separated in two parts considering the human and non-human aspects of C-04, having the groups: C-01, C-02, C-04 (human), C-08 (environmental) and C-04 (non-human), C-05, C-06, C-08 (environmental).
- From the perspective of C-05 (experienced non-human mortality) the dependency group is: C-04 (non-human), C-05, C-06, C-08 (environmental).
- From the perspective of C-06 (potential non-human mortality) the dependency group is: C-04 (non-human), C-05, C-06, C-08 (environmental).
- From the perspective of C-08 (external consequences cost) the dependency group is: C-01, C-02, C-03, C-04, C-05, C-06, C-08 (environmental and non-environmental), C-09. These dependencies can be separated in two parts considering the environmental and non-environmental aspects of C-08, having: C-08 (non-environmental), C-09 and C-01, C-02, C-03, C-04, C-05, C-06, C-08 (environmental). If the distinction between C-04 human and C-04 non-human is also considered, then the dependencies can be separated into three groups: C-08 (non-environmental), C-09, and C-01, C-02, C-03, C-04 (human), C-08 (environmental), and C-04 (non-human), C-05, C-06, C-08 (environmental).
- From the perspective of C-09 (people affected by loss of energy supply) the dependency group is: C-08 (non-environmental), C-09.

It can be seen that some groups show equal connections among the involved indicators. From the logical point of view, the group of indicators is counted only once. The cases are:

- From the perspective of C-01 and C-04 (human).
- From the perspective of C-04 (non-human), C-05, C-06, and C-08 (environmental) with C-04 (non-human).
- From the perspective of C-08 (non-environmental), and C-09.
- From the perspective of C-08 (environmental) with C-04 (human), and C-02.

Thus, the combinations to be modelled are 5:

1. C-01, C-02, C-04 (human), C-08 (environmental).
2. C-01, C-02, C-03, C-04 (human), C-08 (environmental).
3. C-04 (non-human), C-05, C-06, C-08 (environmental).
4. C-02, C-03, C-08 (environmental).
5. C-08 (non-environmental), C-09.

It must be stated at this stage that fixing the relations among the indicators introduces expert judgment, and thus subjectivity, into the process. It is anyhow a limited amount of subjectivity if compared with the allocation of weights as required by usual MCDA methods.

Nevertheless, it must be stated that this is just the assumption of the author. Another person could have a different opinion, supported by his/her different experience, knowledge, and background. Anyhow, once arranged, the relations are going to determine the model and they are not further changed.

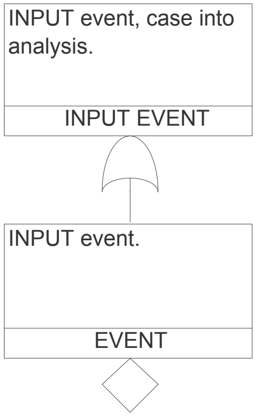


Figure 6.4.2: Tree representing the input event, which is represented by a basic event that could be further developed (diamond symbol) (Colli et al., 2008).

Once identified and defined, the discussed interdependencies are translated into fault tree structures, where dependencies and independencies corresponds respectively to AND and OR gates in the model (see from Figure 6.4.3 to Figure 6.4.13).
For simulation and modelling purposes, an additional tree representing the input event has been added (Figure 6.4.2). This tree is linked to the initiating event in the event tree shown in Figure 6.4.14.
The model is now ready to be processed by the simulation program. Performing sequence analysis using Risk Spectrum software (© Relcon Scandpower AB), it is possible to define the minimal cutsets (MCS) for every single event tree and for the complete model.
Each developed fault tree has the following number of MCS:

- Choice of technology: 5 MCS.
- Material/energy release: 5 MCS.
- Exposure to material/energy: 4 MCS.
- Consequences: 158 MCS

The complete model presents 69 basic events, and a number of 15.800 MCS.
The model has been tested for convergence and it has been successful.

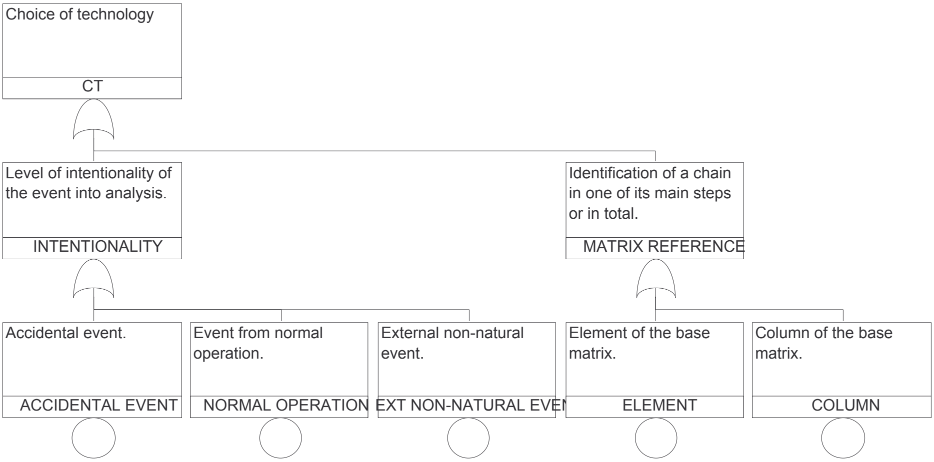


Figure 6.4.3: Tree representing the step choice of technology.

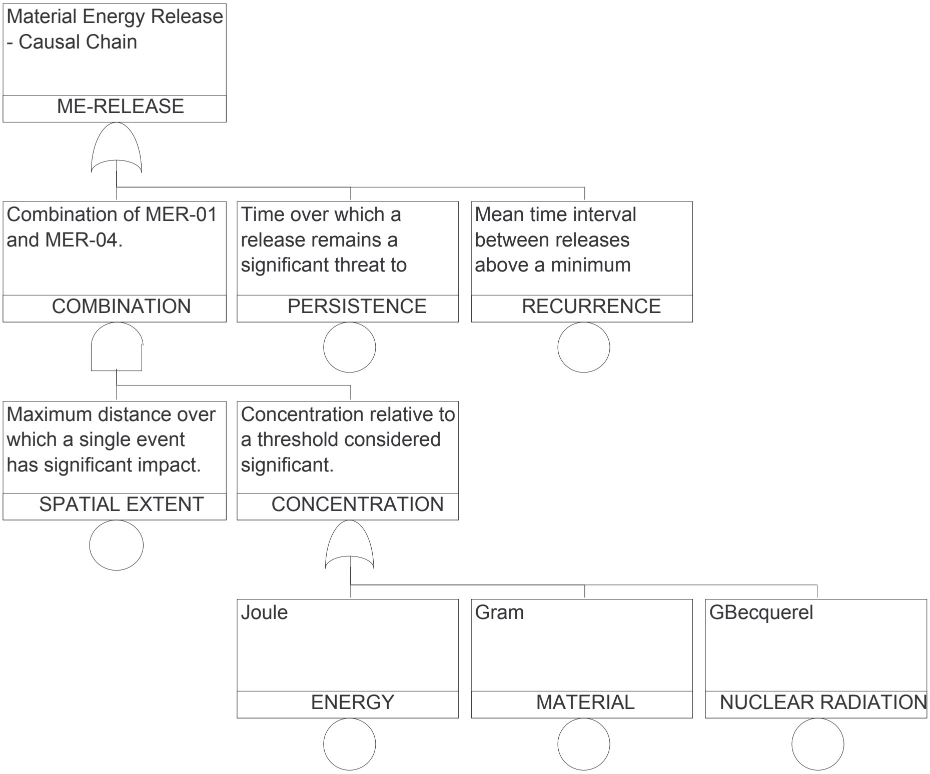


Figure 6.4.4: Tree representing the step material/energy release.

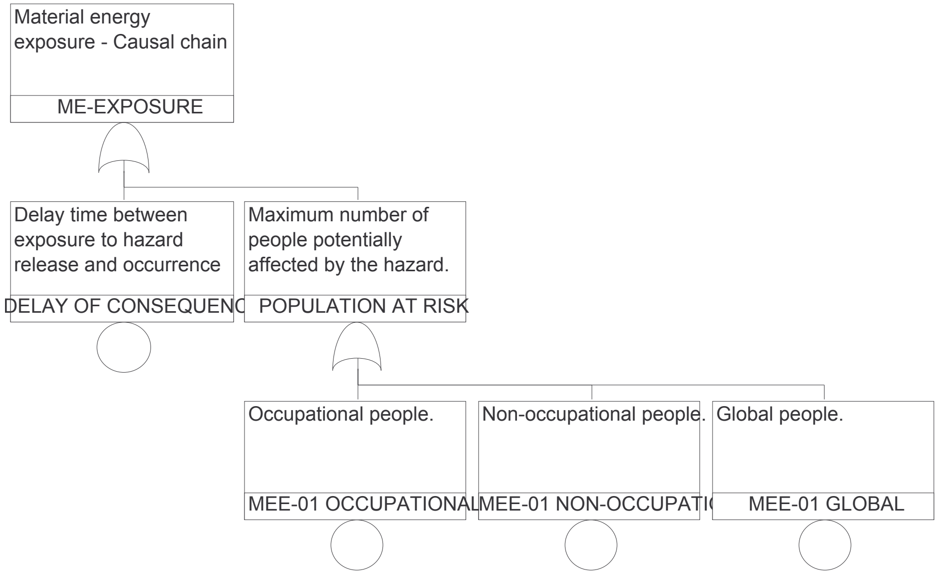


Figure 6.4.5: Tree representing the step material/energy exposure.

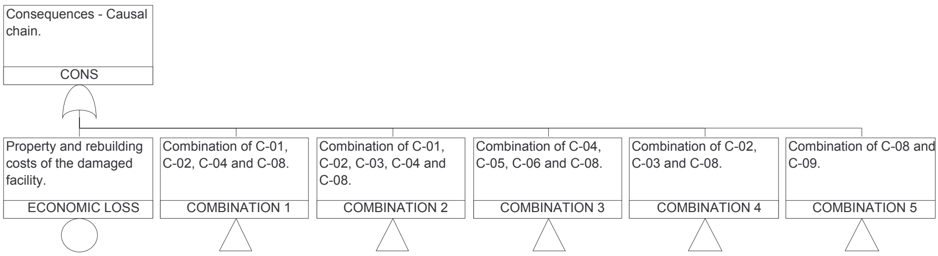


Figure 6.4.6: Tree representing the consequences step. The triangles represent the transfer to the further development of the branch. The combinations from 1 to 5 are shown in the following Figure 6.4.7 to Figure 6.4.11.

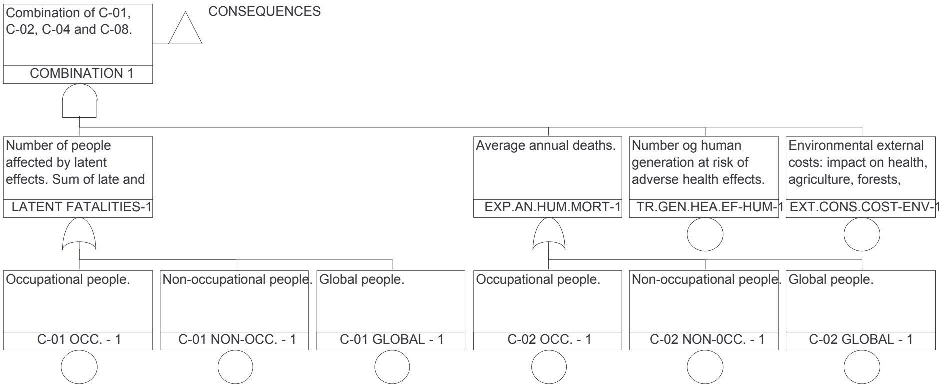


Figure 6.4.7: Tree representing combination 1 from the consequences tree.

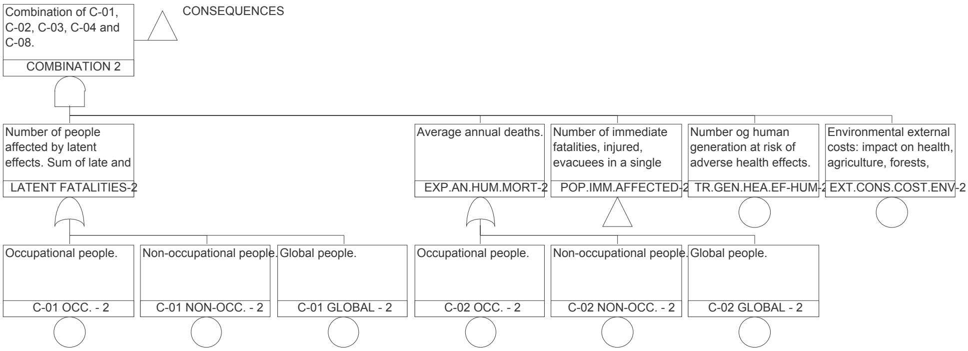


Figure 6.4.8: Tree representing combination 2 from the consequences tree. The development of the branch corresponding to the triangle transfer is shown in Figure 6.4.12.

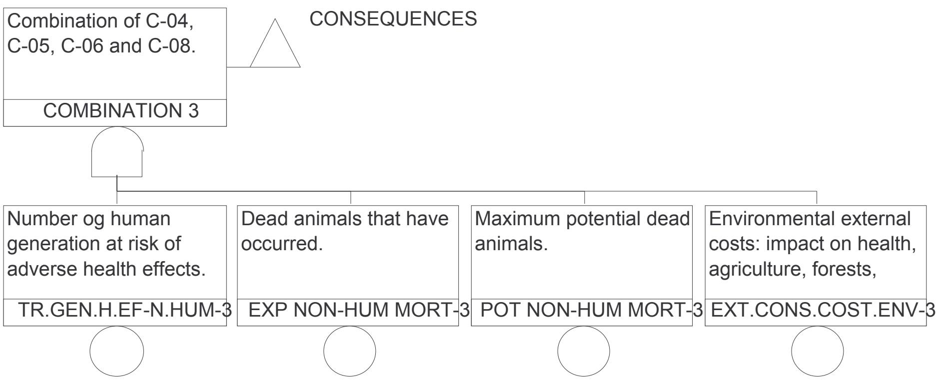


Figure 6.4.9: Tree representing combination 3 from the consequences tree.

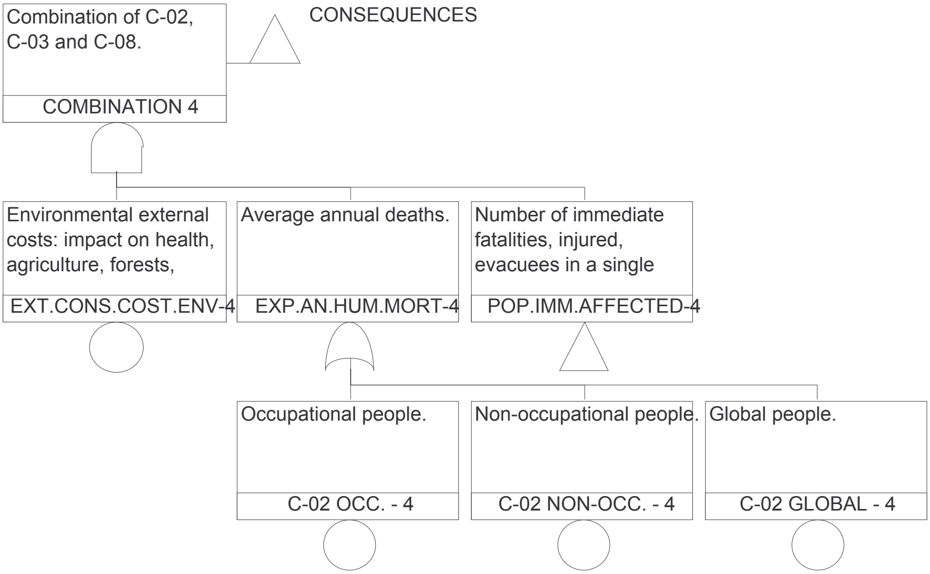


Figure 6.4.10: Tree representing combination 4 from the consequences tree. The development of the branch corresponding to the triangle transfer is shown in Figure 6.4.13.

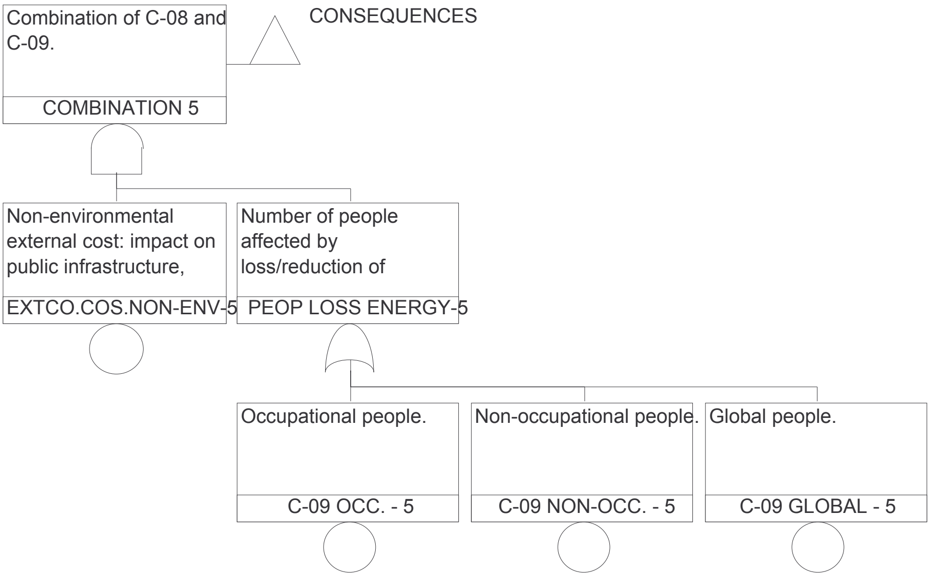


Figure 6.4.11: Tree representing combination 5 from the consequences tree.

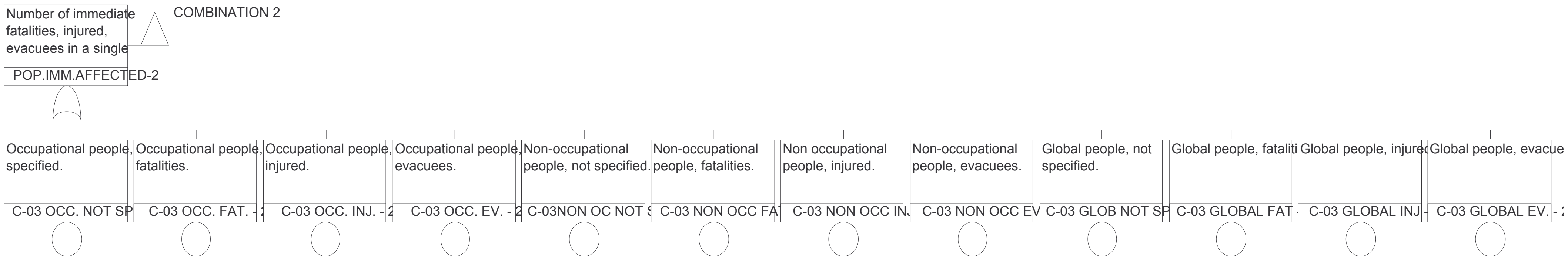


Figure 6.4.12: Tree representing population immediately affected from combination 2.

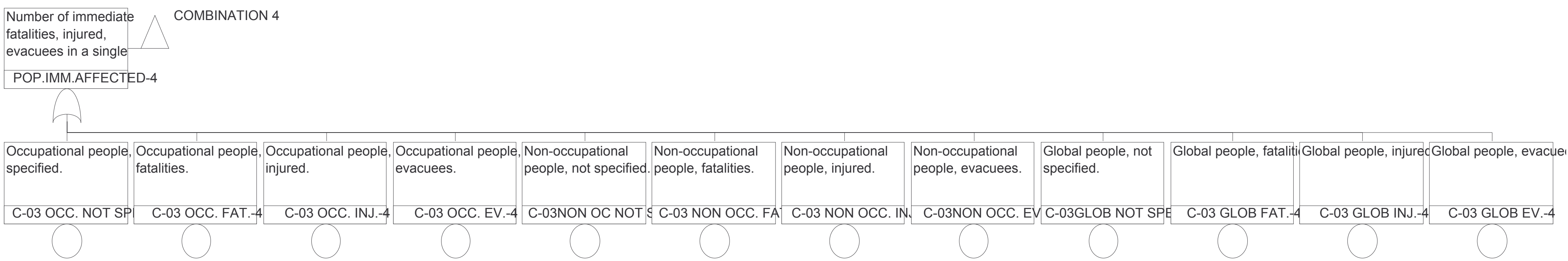


Figure 6.4.13: Tree representing population immediately affected from combination 4.

Input event in the decision event tree.	Choice of technology.	Material Energy Release.	Material Energy Exposure.	Consequences.				
INPUT	CT	MER	MEE	C	No.	Freq.	Conseq.	Code
					1			
					2			C
					3			MEE
					4			MEE-C
					5			MER
					6			MER-C
					7			MER-MEE
					8			MER-MEE-C
					9			CT
					10			CT-C
					11			CT-MEE
					12			CT-MEE-C
					13			CT-MER
					14			CT-MER-C
					15			CT-MER-MEE
					16	3,52E-01		CT-MER-MEE-C

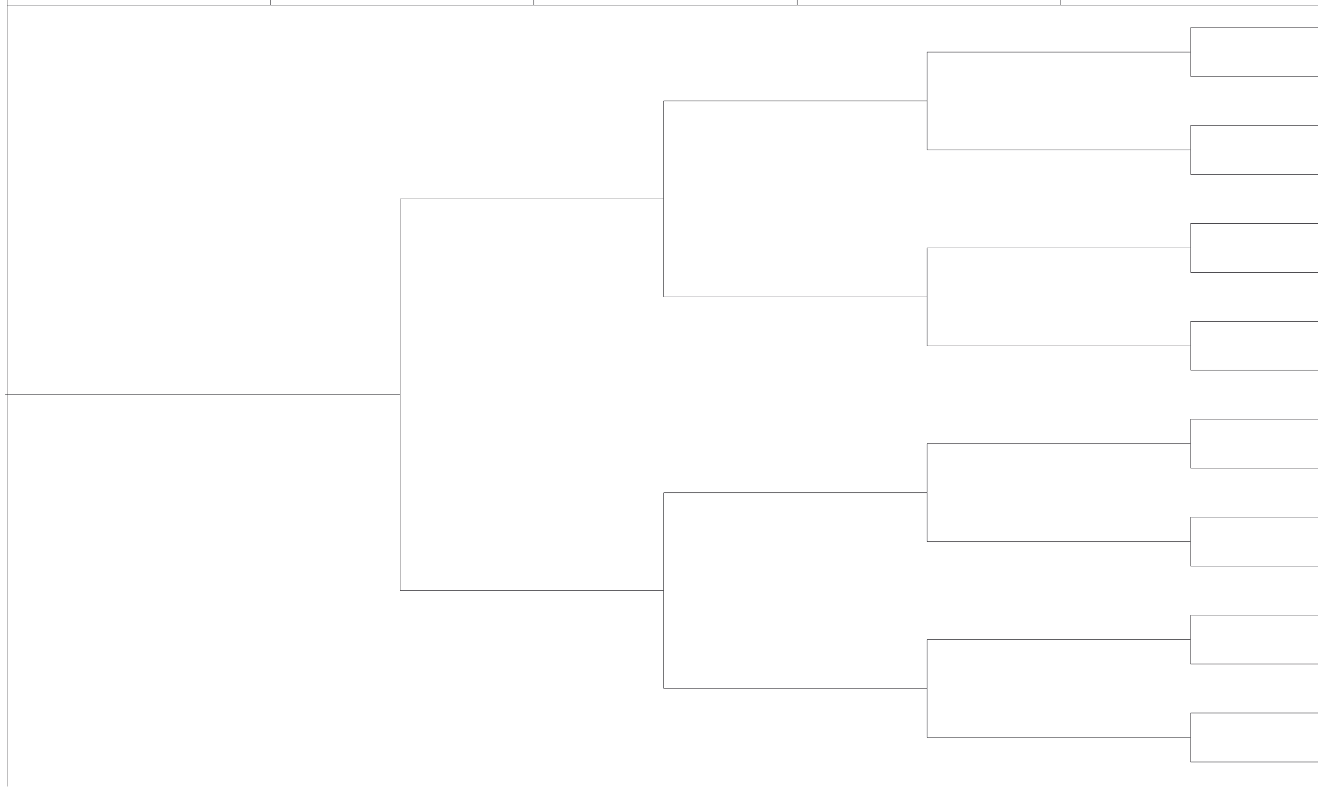


Figure 6.4.14: Event tree of the model.

6.5. The grouping and ranking procedure step-by-step.

The aim of this section is to describe, from a theoretical perspective, the complete grouping and ranking methodology, starting from the application of the RCIs, passing through the simulation, and elaborating the results to reach the final ranking of the events hypothetically applied.

The complete procedure is a chain of eighteen steps, as shown in Figure 6.5.1. The route is shown only once, but it must be stressed and remembered that two parallel procedures should be considered, one for verbal-based applications and one for numerical-based applications.

Let's enter now in the discussion of each single step.

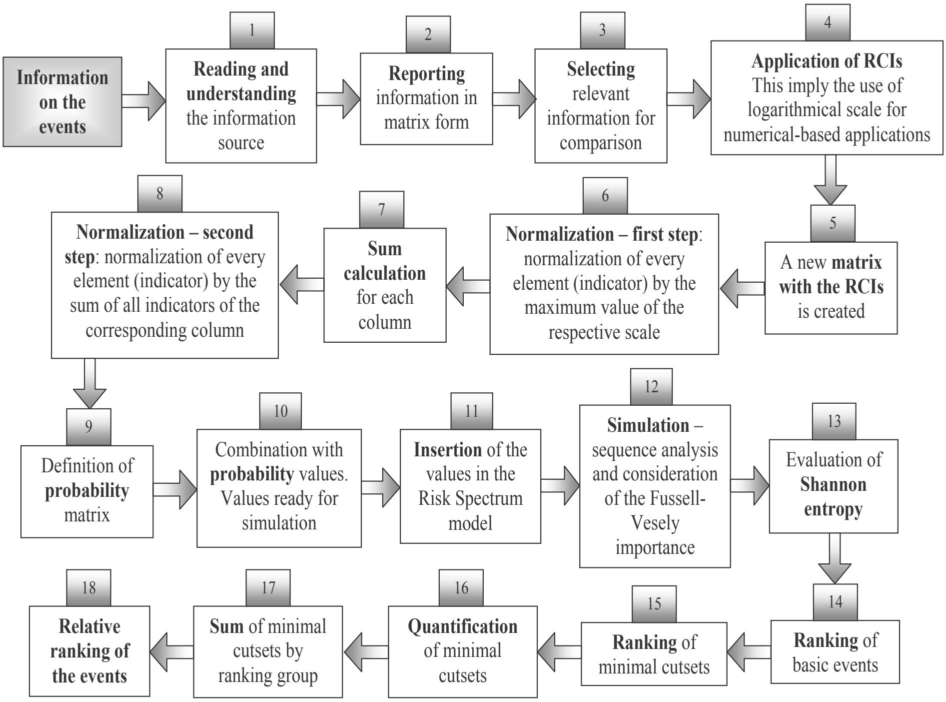


Figure 6.5.1: Step-by-step explanation of the process starting from the source of information, and leading to the relative risk ranking of the events into analysis, passing through the application of the RCIs.

Step 1: Reading and understanding the source of information.

When the purpose is to process a certain amount of events for comparison using the presented approach, the first step should be the investigation of the available sources of information (reports, books, databases, etc) to identify what could be relevant for application. Once this identification is done, the available data are organized (in the following step 2) in a matrix format.

Step 2: Reporting information in matrix form.
All relevant information is reported in a matrix-like form, where every row refers to a specific indicator, and every column to a specific event.
The matrix is composed of elements x_{ij}, where:
i= 1…V, number of criteria (indicators).
j= 1…N, number of events into comparison.

$$\begin{bmatrix} x_{11} & x_{12} & x_{13} & \dots & x_{1N} \\ x_{21} & x_{22} & x_{23} & \dots & x_{2N} \\ x_{31} & x_{32} & x_{33} & \dots & x_{3N} \\ \dots & \dots & \dots & \dots & \dots \\ x_{V1} & x_{V2} & x_{V3} & \dots & x_{VN} \end{bmatrix} \qquad (6.1)$$

Some element could not be filled with information, thus they appear as NA.

$$\begin{bmatrix} x_{11} & x_{12} & x_{13} & \dots & x_{1N} \\ x_{21} & x_{22} = NA & x_{23} & \dots & x_{2N} \\ x_{31} & x_{32} = NA & x_{33} & \dots & x_{3N} = NA \\ \dots & \dots & \dots & \dots & \dots \\ x_{V1} = NA & x_{V2} = NA & x_{V3} = NA & \dots & x_{VN} = NA \end{bmatrix} \qquad (6.2)$$

It is a matrix VxN, square or not (V could be =N, or not).

Step 3: Selecting relevant information for comparison.
To perform consistent comparisons avoiding unbalanced results and difficulties in the grouping and ranking process, all the events involved should have the same amount of indicators involved. This leads to eliminating all NA elements, and thus all the rows including them. In result, only rows with information for all N events under comparison are maintained. The new matrix is:

$$\begin{bmatrix} x_{11} & x_{12} & x_{13} & \dots & x_{1N} \\ x_{21} & x_{22} & x_{23} & \dots & x_{2N} \\ x_{31} & x_{32} & x_{33} & \dots & x_{3N} \\ \dots & \dots & \dots & \dots & \dots \\ x_{M1} & x_{M2} & x_{M3} & \dots & x_{MN} \end{bmatrix} \qquad (6.3)$$

The number of indicators involved is now M≤V.

Step 4: Application of RCIs.
At this stage, the process needs a distinction between the verbal-based and the numerical-based application. In case of verbal-based application, the appropriate level of the 1-to-6 scale is selected according to the related information.

On the other side, for the numerical-based application each element of the matrix is processed according to the formula:

$$I_{ij} = Log_{10}(x_{ij} + 10) \qquad (6.4)$$

Step 5: A new matrix with the RCIs is created.
A new matrix with the resulting values for the RCIs is created. The matrix is composed of elements I_{ij}, where:
i= 1, 2, 3, …M, number of criteria (indicators).
j= 1, 2, 3, …N, number of events into comparison.

$$\begin{bmatrix} I_{11} & I_{12} & I_{13} & \ldots & I_{1N} \\ I_{21} & I_{22} & I_{23} & \ldots & I_{2N} \\ I_{31} & I_{32} & I_{33} & \ldots & I_{3N} \\ \ldots & \ldots & \ldots & \ldots & \ldots \\ I_{M1} & I_{M2} & I_{M3} & \ldots & I_{MN} \end{bmatrix} \qquad (6.5)$$

Step 6: Normalization – first step.
The matrix (6.5) is now processed for normalization. Given the differences in the evaluation scale of the RCIs, the consequence is that the resulting values obtained by the initial application of the indicators could be inhomogeneous according to the scales, which could have different upper limits. In fact, numerical-based applications of the RCIs have scales mostly 1-to-10, but few indicators have scales 1-to-7 and 1-to-8. To avoid inconsistency in the comparison and reach homogeneous numbers, the values are normalized according to two steps. In addition, to ensure the parallel approach for both applications, the 2-steps normalization is executed also for the verbal-based evaluation.
The first step is the normalization of every row according to the maximum of the scale related to the corresponding indicator.
In a general form the process is:

$$\begin{bmatrix} I_{11} & I_{12} & I_{13} & \dots & I_{1N} \\ 0 & 0 & 0 & \dots & 0 \\ 0 & 0 & 0 & \dots & 0 \\ \dots & \dots & \dots & \dots & \dots \\ 0 & 0 & 0 & \dots & 0 \end{bmatrix} \cdot \frac{1}{\max_1} + \begin{bmatrix} 0 & 0 & 0 & \dots & 0 \\ I_{21} & I_{22} & I_{23} & \dots & I_{2N} \\ 0 & 0 & 0 & \dots & 0 \\ \dots & \dots & \dots & \dots & \dots \\ 0 & 0 & 0 & \dots & 0 \end{bmatrix} \cdot \frac{1}{\max_2} + \dots +$$

$$+ \begin{bmatrix} 0 & 0 & 0 & \dots & 0 \\ 0 & 0 & 0 & \dots & 0 \\ 0 & 0 & 0 & \dots & 0 \\ \dots & \dots & \dots & \dots & \dots \\ I_{M1} & I_{M2} & I_{M3} & \dots & I_{MN} \end{bmatrix} \cdot \frac{1}{\max_M} =$$

$$= \begin{bmatrix} \frac{I_{11}}{\max_1} & \frac{I_{12}}{\max_1} & \frac{I_{13}}{\max_1} & \dots & \frac{I_{1N}}{\max_1} \\ \frac{I_{21}}{\max_2} & \frac{I_{22}}{\max_2} & \frac{I_{23}}{\max_2} & \dots & \frac{I_{2N}}{\max_2} \\ \frac{I_{31}}{\max_3} & \frac{I_{32}}{\max_3} & \frac{I_{33}}{\max_3} & \dots & \frac{I_{3N}}{\max_3} \\ \dots & \dots & \dots & \dots & \dots \\ \frac{I_{M1}}{\max_M} & \frac{I_{M2}}{\max_M} & \frac{I_{M3}}{\max_M} & \dots & \frac{I_{MN}}{\max_M} \end{bmatrix} =$$

$$= \begin{bmatrix} I_{11}' & I_{12}' & I_{13}' & \dots & I_{1N}' \\ I_{21}' & I_{22}' & I_{23}' & \dots & I_{2N}' \\ I_{31}' & I_{32}' & I_{33}' & \dots & I_{3N}' \\ \dots' & \dots' & \dots' & \dots & \dots' \\ I_{M1}' & I_{M2}' & I_{M3}' & \dots & I_{MN}' \end{bmatrix} \qquad (6.6)$$

Step 7: Sum calculation for each column.
From the resulting matrix (6.6), the sum of every column is calculated.

$$
\begin{aligned}
I_{11}' + I_{21}' + I_{31}' + \ldots + I_{M1}' &= S_1 \\
I_{12}' + I_{22}' + I_{32}' + \ldots + I_{M2}' &= S_2 \\
&\ldots \\
I_{1N}' + I_{2N}' + I_{3N}' + \ldots + I_{MN}' &= S_N
\end{aligned}
\tag{6.7}
$$

<u>Step 8</u>: Normalization – second step.

In the second step of normalization every element of the resulting matrix (6.6) is divided by the sum of the corresponding column, as from (6.7).

$$
\begin{bmatrix} I_{11}' & 0 & 0 & \ldots & 0 \\ I_{21}' & 0 & 0 & \ldots & 0 \\ I_{31}' & 0 & 0 & \ldots & 0 \\ \ldots & \ldots & \ldots & \ldots & \ldots \\ I_{M1}' & 0 & 0 & \ldots & 0 \end{bmatrix} \cdot \frac{1}{S_1} + \begin{bmatrix} 0 & I_{12}' & 0 & \ldots & 0 \\ 0 & I_{22}' & 0 & \ldots & 0 \\ 0 & I_{32}' & 0 & \ldots & 0 \\ \ldots & \ldots & \ldots & \ldots & \ldots \\ 0 & I_{M2}' & 0 & \ldots & 0 \end{bmatrix} \cdot \frac{1}{S_2} +
$$

$$
+ \ldots + \begin{bmatrix} 0 & 0 & 0 & \ldots & I_{1N}' \\ 0 & 0 & 0 & \ldots & I_{2N}' \\ 0 & 0 & 0 & \ldots & I_{3N}' \\ \ldots & \ldots & \ldots & \ldots & \ldots \\ 0 & 0 & 0 & \ldots & I_{MN}' \end{bmatrix} \cdot \frac{1}{S_N} =
$$

$$
= \begin{bmatrix} \frac{I_{11}'}{S_1} & \frac{I_{12}'}{S_2} & \frac{I_{13}'}{S_3} & \ldots & \frac{I_{1N}'}{S_N} \\ \frac{I_{21}'}{S_1} & \frac{I_{22}'}{S_2} & \frac{I_{23}'}{S_3} & \ldots & \frac{I_{2N}'}{S_N} \\ \frac{I_{31}'}{S_1} & \frac{I_{32}'}{S_2} & \frac{I_{33}'}{S_3} & \ldots & \frac{I_{3N}'}{S_N} \\ \ldots & \ldots & \ldots & \ldots & \ldots \\ \frac{I_{M1}'}{S_1} & \frac{I_{M2}'}{S_2} & \frac{I_{M3}'}{S_3} & \ldots & \frac{I_{MN}'}{S_N} \end{bmatrix} =
$$

$$= \begin{bmatrix} I_{11}'' & I_{12}'' & I_{13}'' & \dots & I_{1N}'' \\ I_{21}'' & I_{22}'' & I_{23}'' & \dots & I_{2N}'' \\ I_{31}'' & I_{32}'' & I_{33}'' & \dots & I_{3N}'' \\ \dots & \dots & \dots & \dots & \dots \\ I_{M1}'' & I_{M2}'' & I_{M3}'' & \dots & I_{MN}'' \end{bmatrix} \quad (6.8)$$

Step 9: Definition of probability matrix.

To obtain risk values, as requested by the aim of the methodology, every element in the previous resulting matrix (6.8) should be composed with probability. The probability matrix must be defined, and it is:

$$\begin{bmatrix} p_{11} & p_{12} & p_{13} & \cdots & p_{1N} \\ p_{21} & p_{22} & p_{23} & \cdots & p_{2N} \\ p_{31} & p_{32} & p_{33} & \cdots & p_{3N} \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ p_{M1} & p_{M2} & p_{M3} & \cdots & p_{MN} \end{bmatrix} \quad (6.9)$$

It can be that all probabilities in (6.9) are different.

The probability values should come from the application of the Bayes approach, as discussed in Section 5.6. If needed, different assumptions for probabilities could be introduced, as it has been the case in (Colli et al., 2008).

Step 10: Combination with probability values.

Each element of the previous resulting matrix (6.8) must be composed with the probability value associated to the respective indicator for the particular event, as from (6.9).

$$\begin{bmatrix} I_{11}'' & 0 & 0 & \dots & 0 \\ 0 & 0 & 0 & \dots & 0 \\ 0 & 0 & 0 & \dots & 0 \\ \dots & \dots & \dots & \dots & \dots \\ 0 & 0 & 0 & \dots & 0 \end{bmatrix} \cdot p_{11} + \begin{bmatrix} 0 & I_{12}'' & 0 & \dots & 0 \\ 0 & 0 & 0 & \dots & 0 \\ 0 & 0 & 0 & \dots & 0 \\ \dots & \dots & \dots & \dots & \dots \\ 0 & 0 & 0 & \dots & 0 \end{bmatrix} \cdot p_{12} +$$

$$+ \dots + \begin{bmatrix} 0 & 0 & 0 & \dots & 0 \\ 0 & 0 & 0 & \dots & 0 \\ 0 & 0 & 0 & \dots & 0 \\ \dots & \dots & \dots & \dots & \dots \\ 0 & 0 & 0 & \dots & I_{MN}'' \end{bmatrix} \cdot p_{MN} =$$

$$= \begin{bmatrix} I_{11}'' \cdot p_{11} & I_{12}'' \cdot p_{12} & I_{13}'' \cdot p_{13} & \dots & I_{1N}'' \cdot p_{1N} \\ I_{21}'' \cdot p_{21} & I_{22}'' \cdot p_{22} & I_{23}'' \cdot p_{23} & \dots & I_{2N}'' \cdot p_{2N} \\ I_{31}'' \cdot p_{31} & I_{32}'' \cdot p_{32} & I_{33}'' \cdot p_{33} & \dots & I_{3N}'' \cdot p_{3N} \\ \dots & \dots & \dots & \dots & \dots \\ I_{M1}'' \cdot p_{M1} & I_{M2}'' \cdot p_{M2} & I_{M3}'' \cdot p_{M3} & \dots & I_{MN}'' \cdot p_{MN} \end{bmatrix} =$$

$$= \begin{bmatrix} I_{11}^{p} & I_{12}^{p} & I_{13}^{p} & \dots & I_{1N}^{p} \\ I_{21}^{p} & I_{22}^{p} & I_{23}^{p} & \dots & I_{2N}^{p} \\ I_{31}^{p} & I_{32}^{p} & I_{33}^{p} & \dots & I_{3N}^{p} \\ \dots & \dots & \dots & \dots & \dots \\ I_{M1}^{p} & I_{M2}^{p} & I_{M3}^{p} & \dots & I_{MN}^{p} \end{bmatrix} \tag{6.10}$$

Step 11: Insertion of the values in the Risk Spectrum model.
The values from matrix (6.10) are inserted into the model developed and shown in Section 6.4. The model is now ready for simulation with Risk Spectrum (© Relcon Scandpower AB).

Step 12: Simulation.
The model is processed for sequence analysis using Risk Spectrum (© Relcon Scandpower AB). From the simulation, the MCS are calculated, and the Fussell-Vesely importance of the basic events is considered.
The Fussell-Vesely formula gives the importance of a basic event as the ratio between the top event unavailability based only on the minimal cutsets (MCSs) where the basic event 'i' is included, and the top event unavailability including all minimal cutsets.

$$I_i^{FV} = \frac{Q_{TOP}(MCS_{including(i)})}{Q_{TOP}} \tag{6.11}$$

Step 13: Evaluation of Shannon entropy.
Shannon defined the entropy in communication theory as:

$$H = -K\sum_{i=1}^{n} p_i \cdot \log p_i \tag{6.12}$$

In (6.13) p represents the probability and K a positive constant. Quantities H "*play a central role in information theory as measures of information, choice and uncertainty*" (Shannon, 1948). Entropy allows assessing the level of disorder in the transmission of signals. On the basis of this formula Shannon could define the number of bits to be transmitted in a specific signal.

The Shannon's theorem is also considered by Jaynes when treating probability theory. Jaynes defines probability distributions as carriers of incomplete information. The entropy H is identified as a reasonable measure of the amount of uncertainty represented by a probability distribution (Jaynes, 2003).
On the base of these discussions, and referring also to (Serbanescu, 1991), the calculation of the Shannon entropy in the context of the application of the RCIs follows the formula:

$$|H| = |\omega_i q_i \cdot \ln(\omega_i q_i)| \qquad (6.13)$$

In the entropy equation, q_i are values coming from the matrix (6.10), while w_i are calculated by Risk Spectrum (© Relcon Scandpower AB) according to the Fussell-Vesely formula. Actually, in this application, the Fussell-Vesely importance acts like a weight for the corresponding RCI.
The entropy evaluation gives information about the uncertainty associated to a specific element in connection to the process. In fact the evaluation considers not only to the single indicator analysed (with the term q_i), but also its interconnection within the process (term w_i).

Step 14: Ranking of basic events.
A ranking of the basic events is performed, according to the resulting values of the Shannon entropy. A verbal categorization of the basic events is done following ranking levels high (H), medium (M), and low (L). If necessary from the context of the application, very high (VH) and very low (VL) levels could also be introduced.
The result of this step is actually a grouping procedure for the basic events. In other words, the RCIs are grouped according to their importance in the specific application.

Step 15: Ranking of minimal cutsets.
Following the ranking of basic events defined in step 14, the ranking of the MCS is performed. Also in this context, the ranking is based on a verbal categorization, following ranking levels high (H), medium (M), and low (L), but with different indicative ranges from the previous application in step 14. If necessary from the context of the application, very high (VH) and very low (VL) levels could also be introduced.
The result of this step is actually a grouping procedure for the MCS. In other words, the combinations of RCIs are grouped according to their importance in the specific application.

Step 16: Quantification of minimal cutsets.
The quantification of the MCS is based on the values introduced in the PSA-like model, referring to matrix (6.10).

Step 17: Sum of minimal cutsets by ranking group.
Summing the values of the MCS from step 16, according to their belonging to one of the groups defined in step 15, leads to the quantification of the various groups for each of the N events under analysis.

$$\sum_i MCS_{i1,H} \quad \sum_i MCS_{i1,M} \quad \sum_i MCS_{i1,L} \qquad (6.14)$$

$$\sum_i MCS_{i2,H} \quad \sum_i MCS_{i2,M} \quad \sum_i MCS_{i2,L} \tag{6.15}$$

$$\sum_i MCS_{i3,H} \quad \sum_i MCS_{i3,M} \quad \sum_i MCS_{i3,L} \tag{6.16}$$

…

$$\sum_i MCS_{iN,H} \quad \sum_i MCS_{iN,M} \quad \sum_i MCS_{iN,L} \tag{6.17}$$

Step 18: Relative ranking of the events.
The value of each single event considered that allows it to be ranked according its risk importance, is obtained by summing all the MCS of the specific event. For the N events into consideration, the rank is:

$$\sum_i MCS_{i1} = R_1 \tag{6.18}$$

$$\sum_i MCS_{i2} = R_2 \tag{6.19}$$

$$\sum_i MCS_{i3} = R_3 \tag{6.20}$$

…

$$\sum_i MCS_{iN} = R_N \tag{6.21}$$

At this stage, the N events into analysis can be relatively ranked according to their final risk value; where the ranking is the highest, the level of risk is evaluated accordingly, in a relative view among the events investigated. The $R_{1...N}$ values obtained could also be added among each other to evaluate the risk of the specific energy chain to which they belong.
An application of the complete procedure explained in this section can be found in Part IV, Chapter II, publication III, " Indicators to Compare Risk Expressions, Grouping, and Relative Ranking of Risk for Energy Systems: Application with Some Accidental Events from Fossil Fuels ".

6.6. Limitations of the method.

The most relevant aspect of the PSA-based Boolean logic-related grouping and ranking methodology is the highly reduced level of subjectivity in the process. Excluding the subjectivity related to the probabilities, and the involvement of a certain degree of subjectivity in the definition of the interdependencies of the RCIs for modelling purposes, the model itself is built following the Boolean logic rules of PSA. Thus, the whole ranking and grouping process follows a path with no major added subjectivity from the user.
Anyhow, possible objective weaknesses could be identified.
The practical application of the grouping and ranking methodology, as presented in (Colli et al., 2008), showed some limitations linked to the use of the simulation program in this context. Normally, PSA programs are designed for PSA applications other than with indicators, and thus to deal with low probabilities. On the other side, the values introduced in the program as from the application of the indicators in combination with their probabilities could be higher.

Risk Spectrum simulation software (© Relcon Scandpower AB) is adopted to run the model, and is normally used with low probabilities (order of 10-2 or lower). With the present application the program has to deal with higher probability values, thus limitations could be expected.
A detailed explanation of the limitations associated with the simulation program is given in (Colli et al., 2008) – see Part IV, Chapter II, publication III.
Anyhow, these limitations are not at all affecting both the method and the outcomes, but only mean that the results must be read in relative way and do not have absolute meaning. The ranking values must be evaluated in relative comparison among themselves, just to state the importance of the events from the risk point of view.
The fact of obtaining relative results could be seen as the only real limitations of the methodology. Anyhow, it must be recalled that this problem is also present in the use of common MCDA methods, as the comparison is always limited at the elements into analysis and must be referred to them only.
The possibility to cancel this limit, at least in the context of the Boolean method and the energy risks evaluation, exists and is related to the use of a complete database of accidental events for energy systems. Applying the Boolean ranking method to that complete set of events could lead to the identification of a scale among the registered accidents, allowing the identification of the min and max values. Anyhow, it must be considered that this scale is 'alive' and could change in relation to new extreme events inserted into the supporting database.

6.7. References.

(Bedford & Cooke, 2001) – T. Bedford, R. Cooke, "Probabilistic Risk Analysis. Foundations and Methods", ISBN 0-521-77320-2, Cambridge University Press, 2001.

(Colli et al., 2008) - A. Colli, D. Serbanescu, B.J.M. Ale, "Indicators to Compare Risk Expressions, Grouping, and Relative Ranking of Risk for Energy Systems: Application with Some Accidental Events from Fossil Fuels", Safety Science, 47 (5), pp. 591-607, Elsevier, May 2009, http://dx.doi.org/10.1016/j.ssci.2008.07.022

(Communities and Local Governments UK, 2000) - "DTLR Multi-Criteria Analysis Manual", December 2000, http://www.communities.gov.uk/documents/corporate/pdf/146868.pdf

(Figueira et al., 2005) - José Figueira, Salvatore Greco, Matthias Ehrgott (Eds.), "Multi Criteria Decision Analysis. State of the Art Surveys", ISBN:038723067X, Springer, 2005.

(Haimes, 2004) – Y.Y. Haimes, "Risk Modeling, Assessment, and Management", John Wiley & Sons Inc., second edition, 2004, ISBN 0-471-48048-7.

(Jaynes, 2003) - E.T. Jaynes, "Probability Theory: The Logic of Science", edited by G. Larry Bretthorst, ISBN-13: 9780521592710, ISBN-10: 0521592712, DOI: 10.2277/0521592712, published April 2003.

(Kumamoto & Henley, 1996) – H. Kumamoto, E.J. Henley, "Probabilistic Risk Assessment and Management for Engineers and Scientists", IEEE Press, ISBN 0-7803-6017-6, 1996.

(Linkov et al., 2004) - I. Linkov, A. Varghese, S. Jamil, T.P. Seager, G. Kiker, T. Bridges, "Multi-criteria Decision Analysis: A Framework for Structuring Remedial Decisions at

Contaminated Sites", in "Comparative Risk Assessment and Environmental Decision Making", I. Linkov and A. Ramadan Eds., Kluwer, 2004, pp.15-54.
(Linkov et al., 2006) - I. Linkov, F.K. Satterstrom, G. Kiker, T.P. Seager, T. Bridges, K.H. Gardner, S.H. Rogers, D.A. Belluck, A. Meyer, "Multicriteria Decision Analysis: A Comprehensive Decision Approach for Management of Contaminated Sediments", Risk Analysis, Vol. 26, No. 1, 2006, pp. 61-78, DOI:10.1111/j.1539-6924.2006.00713.x
(Lootsma, 1999) - F.A. Lootsma, "Multi-Criteria Decision Analysis Via Ratio and Difference Judgement", ISBN 0-7923-5669-1, Kluwer Academic Publishers, 1999.
(Miller, 1956) – G.A. Miller, "The Magical Number Seven, Plus or Minus Two: Some Limits on Our Capacity for Processing Information", The Psychological Review, Vol. 63, N.2, pp. 81-97, 1956.
(Ouspensky, 1949) – P. Ouspensky, "In Search of the Miraculous", Harcourt, New York, 1949.
(© Relcon Scandpower AB) - RiskSpectrum® PSA Professional is developed and maintained by Relcon Scandpower AB in Sweden, http://www.riskspectrum.com/
(Saaty, 2004) – T.L. Saaty, "Mathematical Methods of Operations Research", Dover Phoenix Editions, Dover Publications Inc, New York, 0486495698, April 2004.
(Saaty and Ozdemir, 2003) – T.L. Saaty, M.S. Ozdemir, "Why the Magic Number Seven Plus or Minus Two," Mathematical and Computer Modeling, 38, 233–244, 2003 (with M. Ozdemir).
(Saaty, 1980) – T. L. Saaty, "The Analytic Hierarchy Process: Planning, Priority Setting, Resource Allocation", McGraw-Hill, New York, 1980.
(Serbanescu, 1991) – D. Serbanescu, "A new approach to decision making in different phases of PSA studies", in proceedings of the International symposium Use of probabilistic safety assessment for operational safety PSA '91, IAEA –NEA-OECD, Vienna, 1991.
(Serbanescu, 2005a) – D. Serbanescu, "Some insights on issues related to specifics of the use of probability, risk, uncertainty and logic in PRA studies", Int. J. Critical Infrastructures, Vol. 1, Nos. 2/3, 2005.
(Serbanescu, 2005b) – D. Serbanescu, "Risk, Probability and Uncertainty for Complex Technical Systems", European Safety and Reliability Conference (ESREL), Gdynia-Sopot-Gdansk, Poland, 27-30 June 2005.
(Shannon, 1948) – C.E. Shannon, "A Mathematical Theory of Communication", from The Bell System Technical Journal, Vol. 27, pp. 379–423, 623–656, July, October, 1948.
(Tart, 2000) – C.T. Tart, "States of Consciousness", iUniverse.com Inc. (originally published by Dutton), ISBN: 0-595-15196-5, 2000.
(Triantaphyllou, 2002) - E. Triantaphyllou, "Multi-criteria Decision Making Methods: A Comparative Study", ISBN:0792366077, Springer, 2002.
(Wolfram MathWorld) - http://mathworld.wolfram.com/

7. Evaluation of the results.

7.1. Introduction to the concept of uncertainty.

The purpose of this chapter is to provide support in the evaluation of the credibility of the results obtained by the method discussed in details in the previous two chapters.
Initial tests made on the PSA-like model have shown convergence of the results and of the configurations obtained concerning the ranking of the basic events (indicators). The tests conducted include various runs with variation of the probability values inserted in the model, and various consequence categories configurations.
What is necessary now is to evaluate the possible error embedded in the results by evaluating their uncertainty, and thus giving an estimate of how confident we can be in the values obtained. The approach is discussed mainly at methodological level, but in the last section of this chapter, an exemplificative result is given for the numerical application of the method to twelve events related to the extraction level for coal, natural gas, and oil. The same events have been processed in (Colli et al., 2008) – see Part IV, Chapter II, publication III.
There are various classifications of uncertainties in literature, and a good summary can be found in the PhD thesis of J.P. van der Sluijs (van der Sluijs, 1997); in the same work the author itself proposes a two-dimensional classification scheme, categorizing uncertainties by source (uncertainty in input data, uncertainties in conceptual model structure and in technical model structure, and uncertainty about model completeness) and by type (inexactness, unreliability, and ignorance).
Another distinction among different types of uncertainties is present in (Bedford & Cooke, 2001), where five sorts of uncertainties have been identified (aleatory and epistemic uncertainties, parameter uncertainty, model uncertainty, ambiguity, and volitional uncertainty).
A later discussion on uncertainty issues, complemented by the investigation of sensitivity issues in the field of PSA, is available in (Serbanescu, 2008). In the paper, inputs for uncertainty are identified in parameter values, modelling, and the degree of completeness. In this work, a distinction between type A and type B is given for the evaluation of standard random and systematic uncertainty.
Apart of probabilistic studies and proposed models, also laboratory measurements have to deal with uncertainties and their calculations. They mainly follow the procedures exposed in the ISO/IEC Guide 98:1995 (Guide to the expression of uncertainty in measurement (GUM)). In (Cook, 2002) the approach of the GUM guide is applied, and similarly to (Serbanescu, 2008), it is based on two types of uncertainty evaluations: "*A type A evaluation involves the use of methods and applies only to series of observations, for example repeated measurements of the same quantity. A type B evaluation is one using any other means. Type B evaluations may involve the application of both knowledge and experience. It should be noted that the source of the uncertainty does not determine how it is calculated. In other words, type B evaluation does not only apply to uncertainty components arising from "systematic" errors; it can be applied to uncertainty sources that arise from "random" errors. Further, the shape of the distribution which describes the*

error does not determine the evaluation method". The same type A and B approach has been also presented in (Taylor & Kuyatt, 1994), where it is also stated that "*there is not always a simple correspondence between the classification of uncertainty components into categories A and B and the commonly used classification of uncertainty components as "random" and "systematic." The nature of an uncertainty component is conditioned by the use made of the corresponding quantity, that is, on how that quantity appears in the mathematical model that describes the measurement process. When the corresponding quantity is used in a different way, a "random" component may become a "systematic" component and vice versa. Thus the terms "random uncertainty" and "systematic uncertainty" can be misleading when generally applied. An alternative nomenclature that might be used is:*

"component of uncertainty arising from a random effect,"

"component of uncertainty arising from a systematic effect,"

where a random effect is one that gives rise to a possible random error in the current measurement process and a systematic effect is one that gives rise to a possible systematic error in the current measurement process. In principle, an uncertainty component arising from a systematic effect may in some cases be evaluated by method A while in other cases by method B, as may be an uncertainty component arising from a random effect".

Given the variety of types and classifications, considering the point in common and adapting them to the view of the present work, uncertainties are considered as originating from the following parts:

1. Parameters – considering the input values in the process.
2. Model – including conceptual modelling, and the mathematical (numerical) evaluation.
3. Completeness – associated to the completeness of the information provided in output.

The kinds of uncertainties considered in this thesis are:

1. Aleatory: arising because of natural, unpredictable, inherent variation in the performance of the system under study. It is a stochastic, irreducible uncertainty.
2. Epistemic: due to a lack of knowledge about the behaviour of the system or processes identified with the system that is theoretically resolvable. It can be subjective, and it is reducible.

As stated in (Bedford & Cooke, 2001) "*the two sorts of uncertainty differ with respect to learning via the application of Bayes' theorem: epistemic uncertainties relate to those things about which we could learn if we were able; aleatory uncertainties are ones about which we either cannot or choose not to learn*".

7.2. Uncertainty evaluation method.

The evaluation of the uncertainty should be conducted for the various sources identified in the previous section (parameters, model, and completeness). The parameters entering into the comparative method are the risk expressions coming from external studies, databases, reports, etc. The collected information could have various degrees or incompleteness and recording accuracy depending on the source, the collection path, the severity of the event, etc. In the specific case of databases, as also stated in (Hirschberg et al., 1998), the causes may be classified as external or internal to the organization developing a database. Identified external causes are:

1. Policy decisions in the country of origin;
2. Policy decisions on behalf of the country receiving the information;
3. Commercial and military confidentiality;
4. News value.

While internal causes are:

1. Human factors;
2. Organizational factors;
3. Language barriers.

All these factors contribute to having a certain amount of uncertainty implicit in the information available at the beginning of our comparative process. An initial uncertainty evaluation, if not available directly from the source of the information, should be done to estimate the uncertainty level entering the method and constituting a systematic error, which propagates along the methodology.

For the purpose of evaluating the uncertainty of the RCIs-based method proposed in this thesis, the division among the various steps as previously shown in Figure 6.5.1 is used. They represent eighteen actions to carry out to achieve the goal of ranking an event in relation to others, for which the same procedure has to be equally applied.

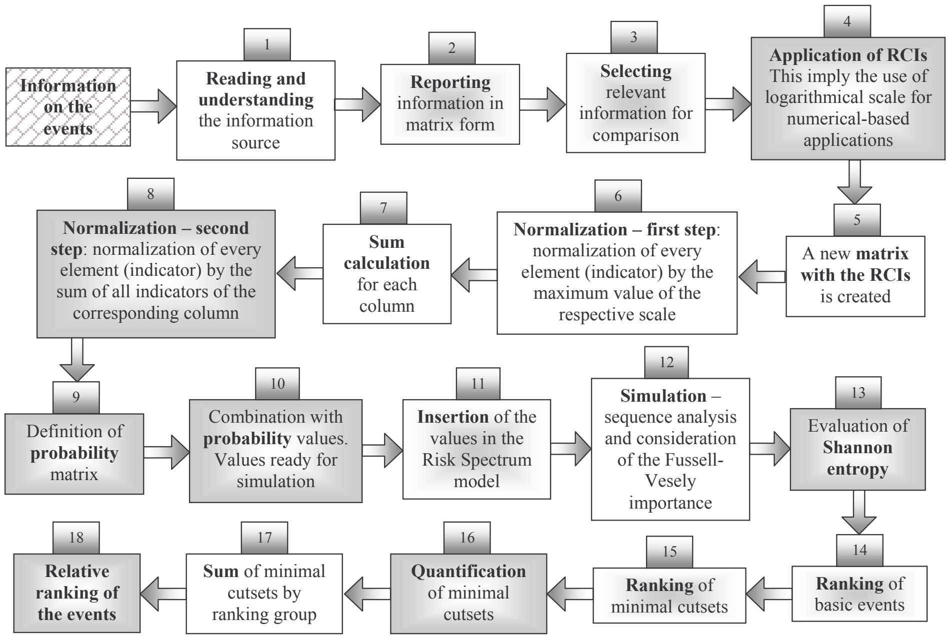


Figure 7.2.1: Steps of the process with highlight on different importance and contribution to the uncertainty calculation. Only highlighted steps are considered, while the white boxes are considered only as conjunction steps and are not counted. Centred highlight=quality approach. Sided highlight=numerical uncertainty calculation.

Among the various identified stages, the level of importance in the evaluation of the total uncertainty is different. Actually, three level of relevance in the uncertainty calculation are identified: some steps can be evaluated numerically, some can be only qualitatively

evaluated, while some others represent only intermediate conjunction steps with limited relevance. The three identified types of steps are differently indicated in Figure 7.2.1.
This distinction is important to decide whether it is necessary to perform an uncertainty calculation, or no calculation is imperative at all.
The following Table 7.2.1 gives more indications about the type of uncertainty evaluation performed. The two significant procedures are the qualitative and the numerical one. They are further discussed in details in the next Sections 7.2.1 and 7.2.2.
As the only uncertainties expressed in numerical form are those associated to the steps 4, 8, 9, 10, 13, 16, and 18, at the end the total combined uncertainty of the whole process is given by the square root of the sum of the square of each single component (Serbanescu, 2008):

$$U = \sqrt{\sum U_4^2 + U_8^2 + U_9^2 + U_{10}^2 + U_{13}^2 + U_{16}^2 + U_{18}^2} \qquad (7.1)$$

Concerning the level of completeness implicit in the information provided by the final result, a connection should be done with the 'completeness' descriptor (CI-01) discussed in Section 5.4.22. Moreover, the selection criteria of the events into analysis have a relevant degree of importance in the consideration of the final results and in the comparison among the events themselves. Implicitly, the uncertainty in the initial input information can influence the level of uncertainty in the completeness of the final information.

Table 7.2.1: Steps of the methodology (according to the steps represented in Figure 7.2.1) and type of uncertainty evaluation associated to each of them.

Step	Type	Action	Comments
1	Intermediate step	No action	
2	Q (quality)	Assumption (no mistake), ISO 9001	V&V (verification & validation)
3	Q (quality)	Assumption (no mistake), ISO 9001	V&V (verification & validation)
4	$U_{ij} = \sqrt{\left(\frac{\Delta y}{y}\right)^2}$ for numerical-based applications $U_{ij} = \sqrt{\left(\frac{x \cdot \ln x}{normalization}\right)^2}$ for verbal-based applications	$U_3 = \sqrt{\sum (U_{ij})^2}$	Calculation
5	Intermediate step	No action	
6	Intermediate step	No action	
7	Intermediate step	No action	

8	$U_{ij} = \sqrt{\left(\frac{\Delta y}{y}\right)^2}$	$U_8 = \sqrt{\sum (U_{ij})^2}$	Calculation
9	$U_{ij} = \sqrt{\left(\frac{\Delta y}{y}\right)^2}$	$U_9 = \sqrt{\sum (U_{ij})^2}$	Calculation
10	$U_{ij} = \sqrt{\left(\frac{\Delta y}{y}\right)^2}$	$U_{10} = \sqrt{\sum (U_{ij})^2}$	Calculation
11	Q (quality)	Assumption (no mistake), ISO 9001	V&V (verification & validation)
12	Intermediate step	No action	
13	$U_{ij} = \sqrt{\left(\frac{\Delta y}{y}\right)^2}$	$U_{13} = \sqrt{\sum (U_{ij})^2}$	Calculation
14	Q (quality)	Assumption (no mistake), ISO 9001	V&V (verification & validation)
15	Q (quality)	Assumption (no mistake), ISO 9001	V&V (verification & validation)
16	$U_{ij} = \sqrt{\left(\frac{\Delta y}{y}\right)^2}$	$U_{16} = \sqrt{\sum (U_{ij})^2}$	Calculation
17	Intermediate step	No action	
18	$U_{ij} = \sqrt{\left(\frac{\Delta y}{y}\right)^2}$	$U_{18} = \sqrt{\sum (U_{ij})^2}$	Calculation

7.2.1. Quality approach.

The steps in which the quality approach has been adopted are 2, 3, 11, 14, and 15 (see Figure 7.1.1). They comprise activities such as reporting risk expressions, selecting useful information, typing values, and ranking results through allocation of the chosen categorizations.

The uncertainty connected to those processes it is difficult to quantify. Anyhow, it is possible to assume that a quality procedure similar to that accepted for ISO 9001:2000 is adopted. With such an approach, the processes follow multiple checking and reviews to guarantee that the possibility of error is minimal.
ISO 9001: 2000 is one of the standards of the ISO 9000 series of quality management systems. ISO 9001 considers the requirements that a quality management system has to satisfy in order to obtain the certification. The links among the main actions with ISO 9001 are shown in Fugure 7.2.1.1.
Clause 4, point 4.1 of ISO 9001 states the "*General requirements*" for a quality management system, for which "*the organization shall:*

a) *Identify the processes needed for the quality management system and their application throughout the organization,*
b) *Determine the sequence and interaction of the processes,*
c) *Determine criteria and methods needed to ensure that both the operation and control of these processes are effective,*
d) *Ensure the availability of resources and information necessary to support the operation and monitoring of these processes,*
e) *Monitor, measure and analyse these processes, and*
f) *Implement actions necessary to achieve planned results and continual improvement of these processes*"(EN ISO 9001: 2000).

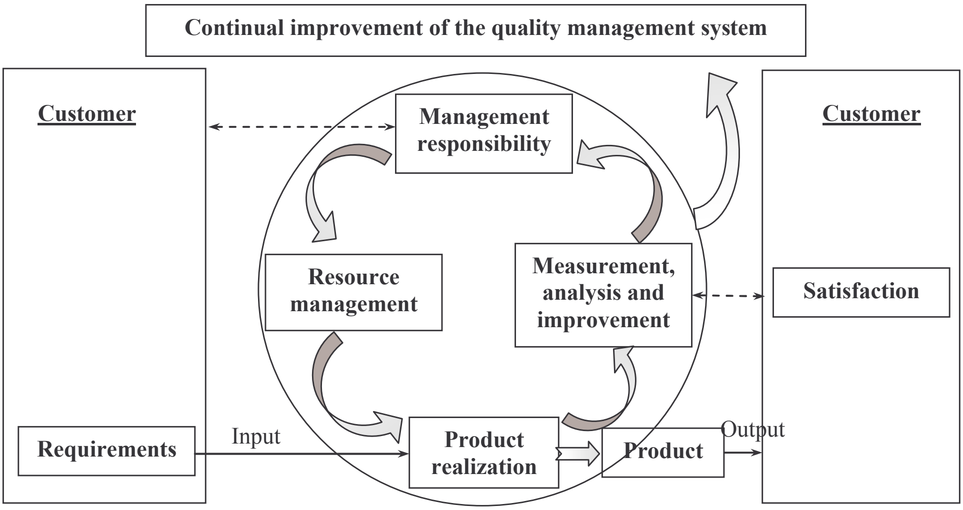


Figure 7.2.1.1: Model of a process-based quality management system (EN ISO 9001: 2000). This illustration shows the connections of the clauses 4 to 8 from ISO 9001. The path identified in the circle means that a continuous improvement of the systems is necessary: this is one of the main requirements of ISO 9001: 2000. In the figure, small arrows (input and output) indicate value-adding activities, while dashed double arrows indicate information flows.

Following the main line of the requirements of the ISO standard, the steps of the method identified as suitable for a qualitative evaluation of the uncertainty are processed for internal and external review. This approach is indicative for future application of the method, but it has also been applied while elaborating the available data for fossil fuels, for

which the results have been published in (Colli et al., 2008). The application has been checked various times, also with a due time gap to allow better identification of personal erroneous actions in processing the diverse operations under examination. The results of the performed processes have been kept available for checking, and the application has been revised internally and externally to the institution in which it has been carried out, the Joint Research Centre (JRC) of the European Commission, Institute for Energy in Petten, Netherlands. The JRC is certified for ISO 9001 (and also ISO 14001) by TNO Certification B.V. (The Netherlands) for the application area of "*execution and management of institutional and competitive research activities to support the European policy-making in the area of energy. Activities covered include also the High Flux Reactor (HFR) related nuclear applications*". Furthermore, the JRC relies on a publication system (Pubsy) which consists of various stages of approval before the publication is accepted.
This procedure, in addition to the stages of external review, can guarantee a verification and validation (V&V) of the obtained results and a minimal possibility of errors in the steps under judgment.

7.2.2. Numerical approach.

The numerical approach has been adopted in steps 4, 8, 9, 10, 13, 16, and 18 (see Figure 7.1.1). For those stages of the methodology application, a numerical uncertainty result is obtained. Having to deal with a single numerical value and not with a distribution of values, the procedure adopted follows that normally applied in experimental physics, when a single measurement from a single instrument is taken. It is assumed that the uncertainty of the single measurement is half the smallest count of the instrument. The relative or fractional uncertainty (U_R) is thus expressed as:

$$U_R = \frac{C_L}{2} \Big/ M$$

Where C_L is the least count of the instrument, and M is the measure taken.
The percentage uncertainty ($U_{\%}$) is:

$$U_{\%} = \left(\frac{C_L}{2} \Big/ M \right) \cdot 100$$

The introduction of Shannon entropy in the uncertainty calculation of step 4 is proposed to possibly measure the potential distortion which could be associated to the evaluation using a qualitative scale (Cox et al., 2005).
Shannon entropy has also a special relevance in assessing the uncertainty of the model, which is actually implicitly quantified in the entropy calculation of step 13.

7.3. Example application.

This example application of the uncertainty evaluation is made with reference to the paper " Indicators to Compare Risk Expressions, Grouping, and Relative Ranking of Risk for Energy Systems: Application with Some Accidental Events from Fossil Fuels" included in Part IV, Chapter II, publication III (Colli et al., 2008).

In the paper three steps of the general chain (Section 3.2, Figure 3.2.1) are taken into account: extraction, treatment, and regional transportation; the involved fuel chains are coal, oil, and natural gas.
In this section, for explicative purposes, the extraction step is analysed, concerning the numerical-based application. The complete uncertainty evaluation of the whole application shown in (Colli et al., 2008) is under publication process with Safety Science.
For the twelve events considered for the extraction step, the input values to process are shown in Table 7.3.1.

Table 7.3.1: Input values for the twelve events considered concerning the extraction step for coal, natural gas, and oil (Hirschberg et al., 1998).

	Coal						**Natural gas**				**Oil**	
RCI	**C-1**	**C-2**	**C-3**	**C-4**	**C-5**	**C-6**	**NG-1**	**NG-2**	**NG-3**	**NG-4**	**O-1**	**O-2**
C-02, global	272	178	106	83	68	65	8	7	5	5	167	51
C-03, global, fat.	272	178	106	83	68	65	8	7	5	5	167	51
C-03, global, inj.	0	0	0	0	0	0	4	6	11	6	0	0
C-03, global, evac.	0	0	0	0	0	0	0	0	0	0	0	0

For the values in Table 7.3.1 the uncertainty has been calculated and can be quantified in 30%.
The data in Table 7.3.1 are then processed according to the eighteen steps of Figure 7.1.1. According to the steps indicated as important point for the uncertainty calculation, for the example application the calculation has been performed for steps 4, 8, 13, 16, and 18.
For the probability related steps 9 and 10, the calculation has been omitted in this particular case, due to the assumptions made regarding probability and explained in (Colli et al., 2008) – see paper in Part IV of this thesis, publication III.
The uncertainty of each investigated step is the following:
Step 4 → 2,8%
Step 8 → 1,6%
Step 13 → 3,1%
Step 16 → 6,7%
Step 18 → 1,7%
The calculation of the total uncertainty follows equation (7.1). The results are different if the uncertainty of the input data is considered or not.
Considering only the five steps listed above, the total uncertainty value is 8,3%. Including also the uncertainty of the input data, the uncertainty value reach 31,5%.
This shows that the input data introduce a level of uncertainty much higher than that of the comparative process itself. They actually introduce a systematic error in the process.

The results show the importance of having good data to obtain reliable results when performing comparisons. The quality of the input data is important, and where possible, it should be always evaluated.
To further validate the accuracy of the uncertainty result, an iterative process is applied to the values of each considered step in the methodology. Each initial numerical value undergoes a variation according to the function:

$$f(x) = V_1(1 \pm U_i \cdot RANDOM) \qquad (7.2)$$

The basic idea of this method is to use the uncertainty ranges of the total uncertainty to calculate the maximum and minimum values of the function (7.2). Those values are then reprocessed for uncertainty calculation to reach another final result. This procedure examines the best and worst case scenarios in the uncertainty result. The results of the fifteen iterations performed are shown in Figure 7.3.1.
Processing various iterations, the total uncertainty varies in a range included between 7,9% and 8,7%, which represent the best and the worst case for our uncertainty within this application.
Considering the trend line, defined as moving average function, it is possible to see that the value of uncertainty, after iteration 9 and few initial transient oscillations, maintain its stability at the value 8,3%, as initially calculated.

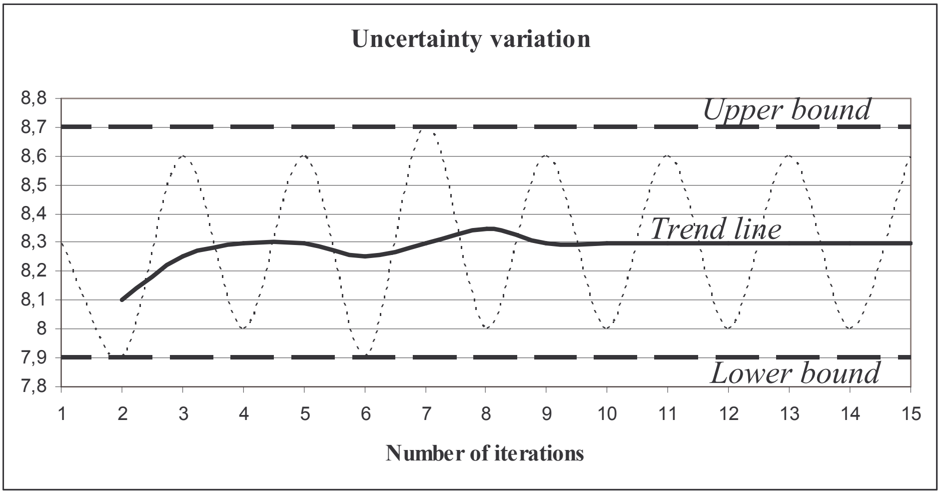


Figure 7.3.1: Uncertainty variation according to the fifteen iterations conducted on the case into analysis. The value of uncertainty remains in the range 7,9 - 8,7, but in the second half of the iterations it stabilizes on the lower value 8 and the upper value 8,6. Considering the trend line (moving average) the value of uncertainty adjust itself to 8,3 % as initially calculated.

7.4. References.

(Bedford & Cooke, 2001) – T. Bedford, R. Cooke, "Probabilistic Risk Analysis. Foundations and Methods", ISBN 0-521-77320-2, Cambridge University Press, 2001.

(Colli et al., 2008) - A. Colli, D. Serbanescu, B.J.M. Ale, “Indicators to Compare Risk Expressions, Grouping, and Relative Ranking of Risk for Energy Systems: Application with Some Accidental Events from Fossil Fuels”, Safety Science, 47 (5), pp. 591-607, Elsevier, May 2009, http://dx.doi.org/10.1016/j.ssci.2008.07.022

(Cook, 2002) - R.R. Cook, "Assessment of Uncertainties of Measurement for Calibration & testing laboratories", Australian National Association of Testing Authorities (NATA), 2nd edition, 2002.

(Cox et al., 2005) – L.A. Cox, D. Babayev, W. Huber, "Some Limitations of Qualitative Risk Rating Systems", Risk Analysis, Vol. 25, No. 3, 2005.

(EN ISO 9001: 2000) – "Quality Management Systems - Requirements" European Committee for Standardization (CEN), December 2000.

(Hirschberg et al., 1998) - S. Hirschberg, G. Spiekerman, R. Dones, "Project GaBE: Comprehensive Assessment of Energy Systems. Severe Accidents in the Energy Sector", First edition, Paul Scherrer Institut, ISSN-1019-0643, (1998).

(Serbanescu, 2008) – D. Serbanescu, "Sensitivity and Uncertainty Issues in the Integrated PRA studies", International Journal of Risk Assessment and Management (IJRAM), Vol.10, No. 1-2, 2008 (2), http://dx.doi.org/10.1504/IJRAM.2008.021053

(Taylor & Kuyatt, 1994) – B.N. Taylor, C.E. Kuyatt, “Guidelines for Evaluating and Expressing the Uncertainty of NIST Measurement Results”, United Sates Department of Commerce, National Institute of Standards and Technology (NIST) Technical Note 1297, 1994.

(van der Sluijs, 1997) – J.P. van der Sluijs, “Anchoring Amid Uncertainty. On the Management of Uncertainties in Risk Assessment of Anthropogenic Climate Change”, University of Utrecht, ISBN 90-393-1329-6, 1997.

8. PSA for new energy systems and its link to the indicators approach.

In this chapter, the framework shown in Figure 2.3.1 has to be recalled. While the previous chapters have been focused on the development of the left-side of the methodology shown in the mentioned figure, the attention is now towards the right-side of the structure, with highlight on the use of probabilistic safety assessment (PSA) techniques for new energy systems (such as some types of renewable energies).

8.1. Using PSA with new energy systems.

The validated use of probabilistic safety assessment (PSA) techniques in the energy sector is mainly limited to the nuclear environment, with applications also in the oil and gas sector.

In the glossary section of (Canadian Nuclear Safety Commission, 2005), the definition which corresponds to PSA in the nuclear field is the following:

"*For a NPP or nuclear fission reactor, a comprehensive and integrated assessment of the safety of the plant or reactor. The safety assessment considers the probability, progression and consequences of equipment failures or transient conditions to derive numerical estimates that provide a consistent measure of safety of the plant or reactor, as follows:*

1. *A Level 1 PSA identifies and quantifies the sequences of events that may lead to the loss of core structural integrity and massive fuel failures;*
2. *A Level 2 PSA starts from the Level 1 results, and analyses the containment behaviour, evaluates the radionuclides released from the failed fuel and quantifies the releases to the environment; and*
3. *A Level 3 PSA starts from the Level 2 results, and analyses the distribution of radionuclides in the environment and evaluates the resulting effect on public health*".

Anyhow, such a methodology could be widely used across all energy systems, and especially in the assessment of new technologies before accidental events happen.

In (Serbanescu et al., 2008) the relevance of PSA is discussed for new application within the nuclear field, but also for modelling risks in non-nuclear energy systems (with reference to the hydrogen energy chain, and the application in the PV industry as described in (Colli et al., 2008)), and to be used in combination with decision theory and energy technology insights in order to deal with complex issues like security of energy supply. The main result of such an analysis is the discovery that the issues encountered in the use of the PSA approach in nuclear and non-nuclear applications are similar.

The objectives and uses of PSA are clearly stated in the NUREG 2300 "Guide to the Performance of Probabilistic Risk Assessments for Nuclear Power Plants": "*The probabilistic risk assessment is an analytical technique for integrating diverse aspects of design and operation in order to assess the risk of a particular nuclear power plant and to develop an information base for analyzing plant-specific and generic issues. In achieving these objectives, probabilistic risk assessments serve many purposes. An assessment of the plant-specific risk provides both a measure of potential accident risks to the public and insights into the adequacy of plant design and operation.*

The assessment of the adequacy of plant design and operation is achieved by identifying those sequences of potential events that dominate risk and establishing which features of the plant contribute most to the frequency of such sequences. These plant features may be potential hardware failures, common-mode failures, human errors during testing and maintenance, or procedural inadequacies leading to human errors. Thus a probabilistic analysis reveals the features of a plant that may merit close attention and provides a focus for improving safety. The other objective achieved by a probabilistic risk assessment is the development of an information base for analyzing plant-specific and generic issues. This information base identifies dominant accident sequences and plant features contributing significantly to risk; it also contains the models of the plant developed during the study. Knowledge of the most probable severe accidents could assist the utility and the Nuclear Regulatory Commission in developing strategies for coping with accidents beyond the current design-basis accidents. This information could provide a focus for training operators to deal with such accidents. Emphasis could be placed on diagnosing the most-probable severe accident sequences and on providing information and guidance to the operators on how to cope with such accidents. In addition, the timing and location of containment failure and the magnitude of the potential release and radioactive material are estimated for each accident sequence. This information could be used in developing emergency response plans. Information developed in the assessment could help in making decisions about the allocation of resources for safety improvements, by directing attention to the features that dominate plant risk. The analysis may uncover new issues potentially generic to the industry. The Nuclear Regulatory Commission could use this information to focus its resources on investigating problems most important to safety and eliminating or reducing requirements and the expenditure of resources on issues not important to safety. The plant models developed in the assessment can serve a wide spectrum of uses. They can be used to assess the safety significance of operational occurrences at the plant; they can also be used to assess the applicability and significance of occurrences at other plants. The models provide a basis for evaluating alternative design changes to improve safety. The utility may well find the information and models developed in the study to be useful in training personnel. The analysis draws together diverse aspects of plant design and operation into an integrated model that could provide plant operators and utility engineers with a different perspective that could prove useful in the training of both. In a broader sense, the Nuclear Regulatory Commission has used a collection of PRA studies to evaluate the potential safety value of contemplated regulatory changes and to evaluate generic safety issues. Thus, probabilistic risk assessments provide not only a technique for assessing the safety of a particular facility but also an information base that is applicable to a wide variety of issues and decisions" (NUREG 2300).

It is clear the there is a variety of benefits in using PSA. First of all is the possibility to assess the level of risk associated to a certain installation; moreover, the focus on the design, identifying its weaknesses, makes PSA a valid instrument for evaluation, improvement, and training of involved human resources.

For those reasons, the probabilistic safety analysis has become an important supplement to deterministic analysis in the evaluation and improvement of the safety level of a facility. It can be considered an added value, both for existing areas of application and for new fields.

The use of PSA, in combination with the appropriate development of key parts in the model (e.g., definition of end states), could lead to the identification of consequences and risks for a specific installation. This could give an important contribution in the evaluation of new energy systems, where incidents are maybe rare, or maybe not reported in databases, or maybe listed but not disclosed to the public; in any case, difficultly available for assessing risk.

8.1.1. Limitations of PSA.

Apart from the benefits of using PSA techniques previously discussed, it must be remembered that the PSA application includes also some limitations. The main limitations identified concerns uncertainties.

"*PSA invariably contain uncertainties arising from three main sources:*

- *uncertainties due to a lack of comprehensive data regarding the area under consideration. It is impossible to demonstrate the exhaustiveness of a PSA, even when the scope of the analysis has been extended to as large a number of situations as possible --notably in terms of various reactor operating states and potential initiating events.*
- *uncertainties regarding data. Such uncertainties concern the reliability data for plant components, the frequency of initiating events, common-mode failures and failures resulting from human actions. The main uncertainties are those relating to the frequency of rare initiating events (for example, the combination of a steam piping break and a steam-generator tube break), as well as data relating to human factors.*
- *uncertainties associated with modelling assumptions that cannot easily be quantified, such as the resistance of certain components under accident conditions, poorly understood physical phenomena or human actions.*

In view of these uncertainties, the assumptions on which PSAs are based are designed to ensure sufficient safety margins. It is worth noting that the uncertainties are not intrinsic to PSAs, but may generally be attributed to lack of detailed knowledge. Indeed, one of the benefits of conducting PSAs is that they can identify areas about which we need to learn more" (NEA, 1992).

In (Hirschberg et al., 1998) other limitations are also listed in connection to the use of the PSA technique. The uncertainty of the results from a PSA study could be affected by two types of limitations:

1. Intrinsic, including incompleteness, database, human interactions, common cause failures, and uncertainty.
2. Matters of practice, including consistency, conservatism, human interactions, system-related dependencies, external events, time dependencies, uncertainty, and documentation.

While the intrinsic limitations are addressed as difficult or impossible to overcome, the second type is mainly reducible by improving knowledge and experience.

8.2. The PSA model for PV.

To prove the feasibility of the application of PSA to new energy systems, the model has been developed and the study has been processed for the manufacture industry in the photovoltaic energy area. Various manufacturing techniques are currently adopted for the various types of photovoltaic cells available. The focus of this application is on the multi-crystalline silicon cells production path, being this kind of cells the most widely used in photovoltaic installations.

The idea of applying the PSA approach to the photovoltaic industry originates partly from the background of the Author, and partly from an interesting input arriving from (Fthenakis, 2003), where the use of FT analysis has been suggested by as a method for accident prevention in the photovoltaic cell manufacture industry. The first complete PSA study for the same area has been performed and presented in (Colli et al., 2008), following the approach based on the standards for nuclear industry (NUREG 2300). Unfortunately, due to the lack of data from the PV industry, the PSA model couldn't be developed in deep details. Anyhow the model exists and could be further developed in case of interest.

The PSA study has been done for the process represented in Figure 8.2.1, showing the production of multi-crystalline silicon solar photovoltaic cells step-by-step. A total of thirteen stages have been identified.

The process normally takes place in a very clean environment, to avoid particulate of different types to enter in contact and be fixed onto the cells, thus possibly limit their efficiency. For this reason, it is also possible to find pressure-regulated ambient, where the pressure is maintained slightly above the atmospheric level.

The ambient is also temperature-regulated; temperature is controlled and kept around 20-25°C. This leads to the assumption that also the working temperature of the machineries is around the same level, except where differently indicated. This fixed temperature allows having optimal measurements and/or checking procedures at the testing points along the process. In fact, the crystalline cell performance in terms of electricity and voltage is temperature dependent and inversely proportional to it.

A ventilation system is present and connected at almost every step of the process where chemical vapours, gases, and hot air are released.

The ventilation system takes into consideration two aspects:

1. Ventilation for hot air;
2. Ventilation for chemical substances (with appropriate pollution control equipment, like filters/scrubbers).

Various chemical substances, having different degrees of danger, are used in this manufacture procedure. They enter and are released from the process as shown in Figure 8.2.1.

To build the model to use in the PSA analysis, many tasks have to be accomplished. They are grouped and listed in the mind map shown in Figure 8.2.2. The aim of this map is just to offer the reader an overall picture, giving information on the various performed tasks for a better and easier understanding. Anyhow, it must be stated that the scheme does not really reflect the real interconnections among the various branches, as typical for a PSA study. The mind map is divided into six main branches, listing the fundamental characteristics of the cell manufacturing process, the norms adopted in the study, the principal aspects of the ET/FT modelling, the data sources used for the study, the type of analysis executed, and the results obtained.

Once the model is developed, several runs for consequences analysis are processed using RiskSpectrum® PSA Professional (© Relcon Scandpower AB).

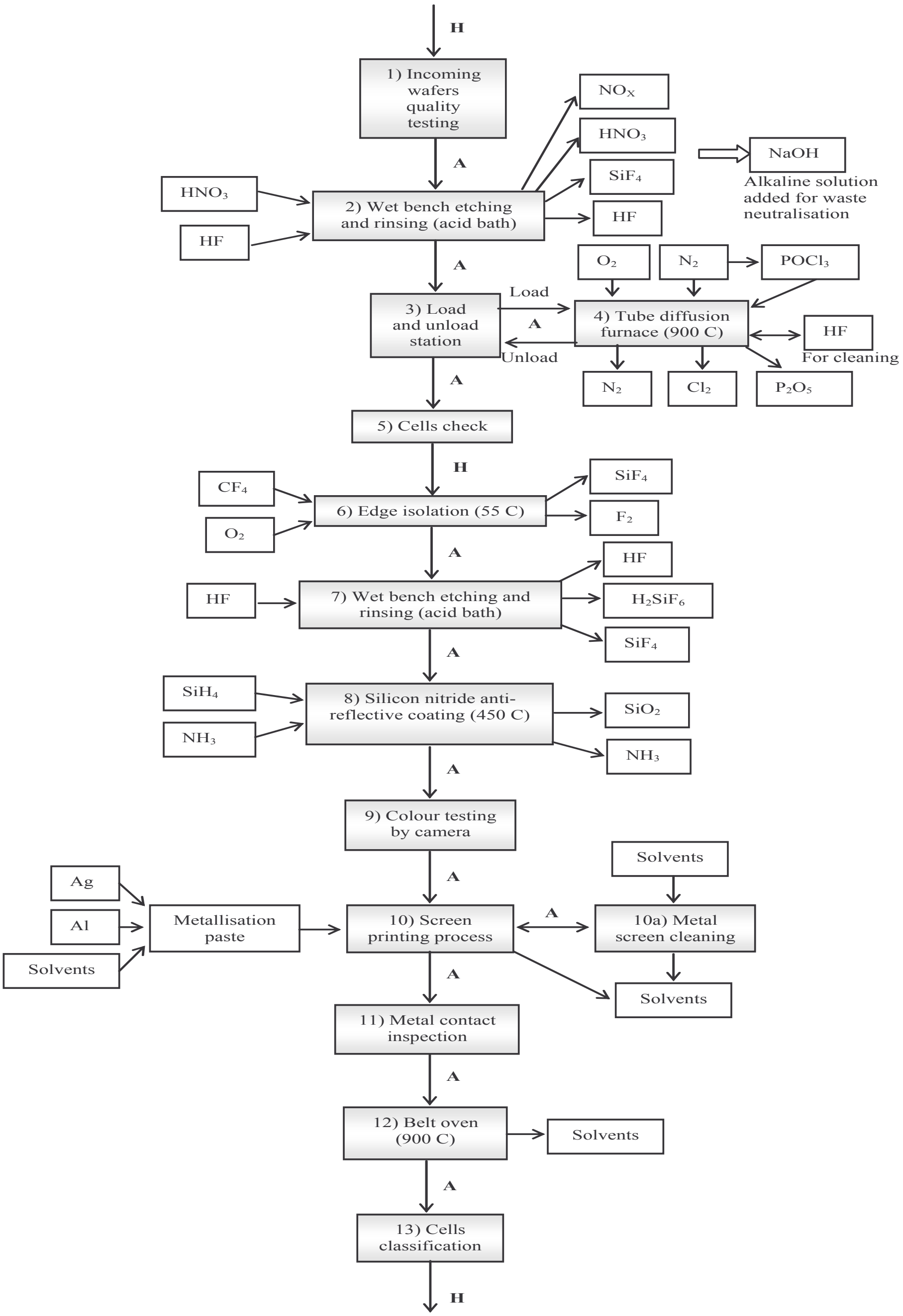


Figure 8.2.1: The multi-crystalline silicon photovoltaic cells manufacture process (H= the process is carried on manually; A= the process is carried on automatically). The most important substances (in terms of use and possible hazard to human health) are shown, as they enter and are released from the process.

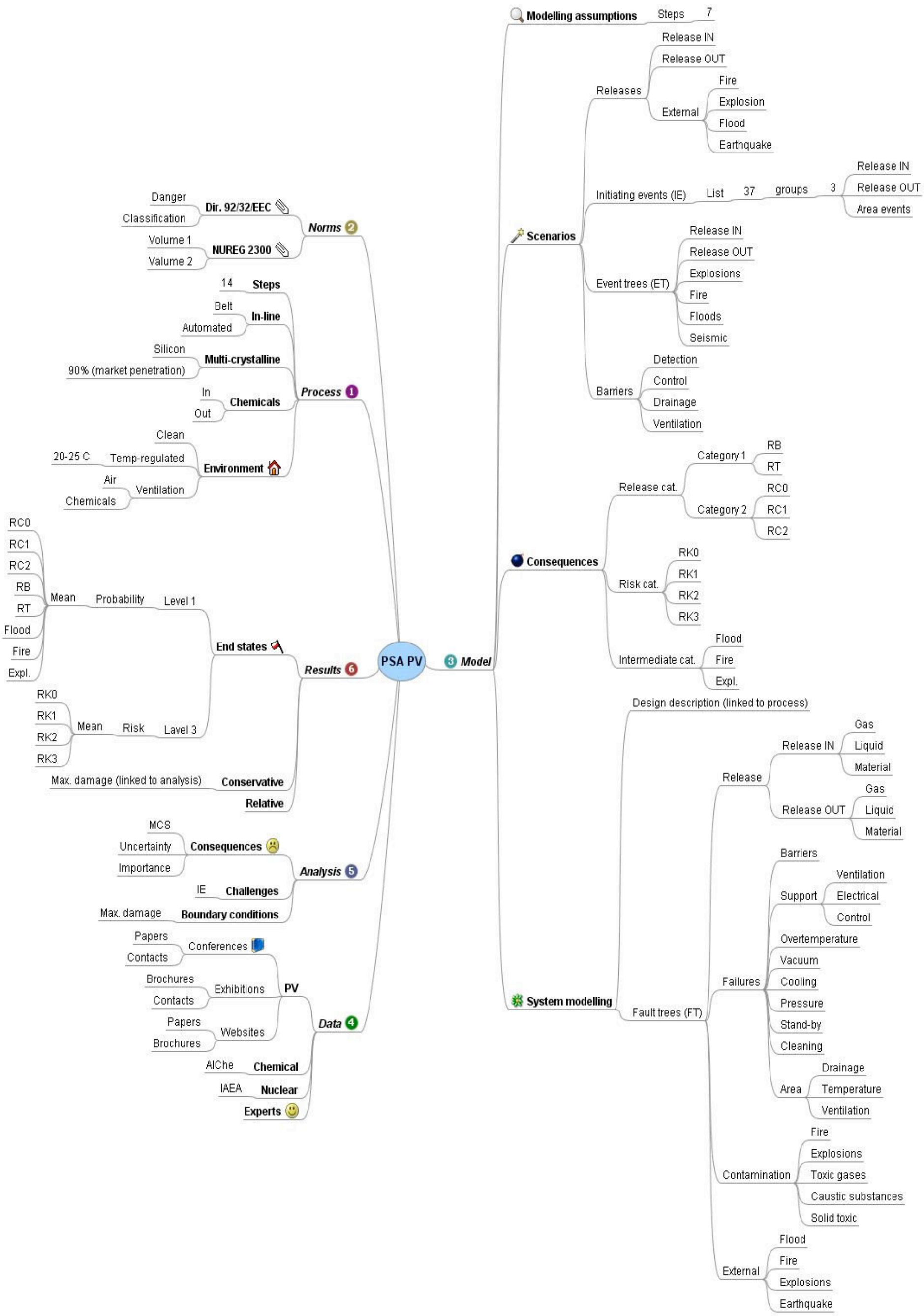
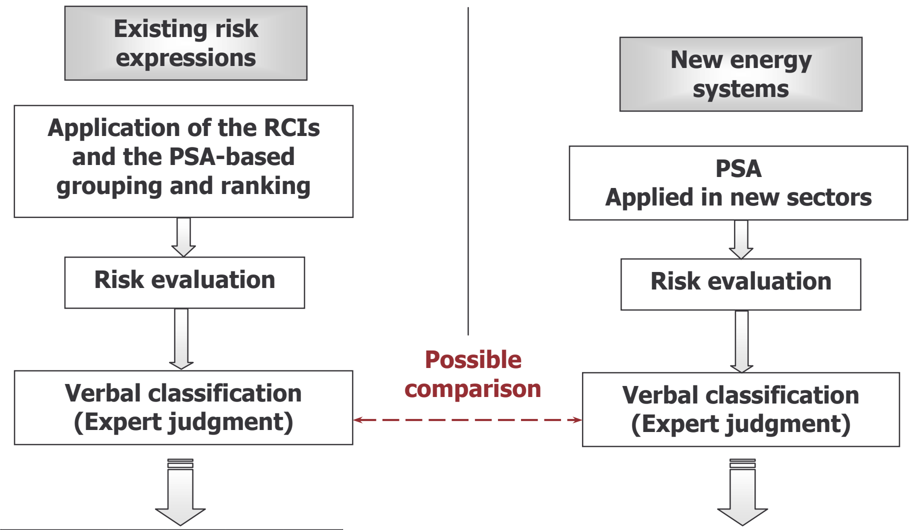


Figure 8.2.2: Mind map of the PSA study for the silicon PV cells manufacturing process into consideration (FreeMind software). The map is useful to offer an overview of the performed tasks, but it is not significant to express the typical interconnections of a PSA study.

The most significant results of the analysis and more details about this work are available in the paper added at the end of this book, in Part IV, Chapter II, publication IV.

8.3. The combination with the RCIs approach.

As initially stated in Section 2.2, the main purpose of this thesis is to develop a comprehensive methodology to allow risk comparison among different energy systems. This means that risks from old and new technologies should also find a way to be compared. It is clear that some new energy sectors do not have databases of reported accidents, which can create difficulties in their risk evaluation, if this is based only on the application of the RCIs.



Events	Ev.1	Ev.2	Ev.3	Ev.4
Release of flammable chemicals	H	M	L	M

Risk category	RK0	RK1	RK2	RK3
Release of silane during process	L	M	M	H
Release of flammable substances during process	L	M	M	H

Figure 8.3.1: The RCIs-based methodology and the application of PSA in the context of new energy systems are two separate approaches, whose results could be compared only at verbal level. The risk evaluation, converted into a verbal categorization based on expert judgment, could be suitable for comparison. Anyhow, the criteria for assigning a specific risk level should be considered for both processes.

The use of PSA techniques has been demonstrated valid also for use in new areas, and the model for the photovoltaic manufacture industry is an example. The identification of risks

by PSA analysis adopting tailored risk categories (as for the case of PV), which creates a link to what in the nuclear sector is defined as PRA level 3, is the base to establish the comparison among the results of a certain PRA study and the results obtained through the application of the RCIs with the Boolean logic-related method.
Two sets of results are thus obtained, which could permit comparison at verbal level. Relying on the expert judgment, a verbal classification (such as high, medium, low) could be obtained for the two sets, allowing comparison.
An example is shown in Figure 8.3.1, considering the results obtained by the PSA analysis on the PV model concerning releases of silane and other flammable substances during the process (according the four considered risk categories), and other four imaginary accidental events about release of flammable chemical substances processed through the RCIs-based method.
During the cross comparison, the criteria for the definition of the verbal risk ranking should be always considered to avoid possible inconsistencies. To give an example, if the left-side method (RCIs) has processed accidental events involving a significant release of flammable chemicals, then the comparison with the right-side approach (PSA) should take into consideration the verbal ranking for the risk category RK3 (RK3 has been defined as "high risk induced by release/spill"; this category involves releases above limits imposed by regulations). The judgment is in any case left to the expert involved, assuming he/she uses a rational approach.
Moreover, during the evaluation, it must be remembered that the level of uncertainty associated to the results from the two different methods is dissimilar.
Finally, it must be stressed that the comparison is always meant in relative sense, among the events into analysis.

8.4. References.

(Canadian Nuclear Safety Commission, 2005) – "Probabilistic Safety Assessment for Nuclear Power Plants", Canadian Nuclear Safety Commission Regulatory Standard S-294, ISBN 0-662-40139-5, April 2005.

(Colli et al., 2008) – A. Colli, D. Serbanescu, B.J.M. Ale, "PRA-Type Study Adapted to the Multi-crystalline Silicon Photovoltaic Cells Manufacture Process", in "Safety, Reliability and Risk Analysis: Theory, Methods and Applications", Martorell et al. (Eds.), Taylor & Francis Group, London, ISBN 978-0-415-48513-5, for ESREL 2008 & 17th SRA Europe Annual Conference, 22-25 September 2008, Valencia, Spain.

(FreeMind software) - http://freemind.sourceforge.net/wiki/index.php/Main_Page

(Fthenakis, 2003) - Fthenakis V.M., 2003, "The Role of Hazard Analysis in PV Manufacture", 3rd World Conference on Photovoltaic Energy Conversion, WCPEC-3, May 12-16, 2003, Osaka, Japan, http://www.pv.bnl.gov/art_169.pdf .

(Hirschberg et al., 1998) - S. Hirschberg, G. Spiekerman, R. Dones, "Project GaBE: Comprehensive Assessment of Energy Systems. Severe Accidents in the Energy Sector", First edition, Paul Scherrer Institut, ISSN-1019-0643, (1998).

(NEA, 1992) – "Probabilistic safety assessment: an analytical tool for assessing nuclear safety", Nuclear Energy Agency (NEA), Issue Brief: An analysis of principal nuclear issues, No. 8, January 1992, http://www.nea.fr/html/brief/brief-08.html

(NUREG 2300) - "A Guide to the Performance of Probabilistic Risk Assessments for Nuclear Power Plants", US Nuclear Regulatory Commission, http://www.nrc.gov/reading-rm/doc-collections/nuregs/contract/cr2300/

(© Relcon Scandpower AB) - RiskSpectrum® PSA Professional is developed and maintained by Relcon Scandpower AB in Sweden, http://www.riskspectrum.com/

(Serbanescu et al., 2008) - D. Serbanescu, A. Colli, A.L. Vetere Arellano, "On some aspects related to the use of integrated risk analyses for the decision making process, including its use in the non-nuclear applications", in "Safety, Reliability and Risk Analysis: Theory, Methods and Applications", Martorell et al. (Eds.), Taylor & Francis Group, London, ISBN 978-0-415-48513-5, for ESREL 2008 & 17th SRA Europe Annual Conference, 22-25 September 2008, Valencia, Spain.

PART III

Conclusion

9. Conclusive evaluation.

9.1. Comparisons of energy risks.

What has been presented along this thesis is one possible methodology to rank risks, processing comparisons among different energy systems.

The complete discussed method allows evaluations based on historical risk expressions for traditional energy systems, as well as the introduction of new energy technologies in the comparative process. The core aspect of this double approach is the use of probabilistic safety assessment (PSA) techniques in two innovative contexts: as a multi criteria decision analysis (MCDA) tool to group indicators and rank events, and as a way to assess the risk level in new areas of application, such as those offered by new energy systems approaching or have just entered the market.

Along the thesis the focus has been mainly maintained on the theoretical development. Anyhow, few possibilities of application have shown a good and reliable response of the presented method.

Even though the first results have been satisfying, some limitations arise from the approach. In a whole view, the limits can be mainly related to the following aspects:

- Subjectivity level.
- Risk characterisation indicators not fully comprehensive.
- Absence of sustainability aspects.

The subjectivity, which shows up at different stages of the whole procedure, can be connected to the choice of the indicators, as well as to the definition of their interconnection and their associated probabilities. This requires the direct involvement of the user, with his/her background, knowledge, experience, personality, etc. Subjectivity is one characteristic, as risk itself could have subjective characteristics.

As second limit, the proposed indicators do not cover comprehensively all the aspects of risk, but are limited to what has been considered more relevant to evaluate risk in the energy sector. This is an aspect connected to subjectivity. Another person, with different ideas and different needs, could change the list of indicators, neglecting some aspects, but highlighting some others which have been set aside in this proposed list. Obviously, changing the indicators, the PSA-like model must be revised accordingly. Anyhow, it is important to stress that the application of the method is not affected and does not change its value.

The third main limit of this procedure is the absence of sustainability aspects. As discussed in (Gray, Wiedemann, 1999), to obtain a clear and complete overview of the effects of human actions on the environment, both risk management and sustainable development should be considered and developed in an interconnected way.

The work of this thesis was born to target the risk aspects associated to various energy systems. Completing this work with the additional energy-related sustainability issues could be part of future investigations.

In the next sections, a careful exploration among benefits and limits of what achieved during this thesis is conducted.

9.1.1. The RCIs.

The RCIs have the main purpose to be applicable to single events (e.g., incidents/accidents) and single pieces of information affecting the various steps along a specific energy chain. Anyhow, when performing a comparison, some criteria must be followed to avoid inconsistencies in the results. The comparison of two or more events should consider the following specifications:

- The events should be related to the same level of the fuel or life cycle into consideration, or, at least, they should take into consideration similar processes.
- The events should be 'technically' similar (e.g. comparison of different explosions concerning natural gas and oil).
- The indicators adopted for the comparison should have obtained a numerical evaluation for all the events into analysis. If one indicator has been filled only for some events, but not for some others, it should then be excluded from the comparative process. Of course, it is not necessary to fill in all the indicators for every event into analysis, but the higher the number of indicators available for the comparison, the more complete the information and the more consistent the obtained outcome will be.
- Wherever available, the information can be applied to the indicators directly in the original format. In some other cases, the information must be elaborated or interpreted from the source to obtain the correct form to be useful for the indicators.

The proposed set of RCIs is actually just one possible list. They have been thought to cover the human, economical and environmental aspects of risk in the context of the energy systems. In fact, they also wanted to be limited in number, to avoid the communication of an excessive amount of information to non experts. It must be remembered that a wide range of stakeholders have been identified as possible receivers of the results obtained through this method. The most important aspects to communicate have been translated into the RCIs. Even though the RCIs are the proposed ones, other risk indicators could be developed, following specific needs of a certain context. As this thesis focuses on the methodology and its relevance, it must be said that in case the set of risk indicators should be changed, the methodology in itself and in its validity won't be affected.

9.1.2. The grouping and ranking PSA-based Boolean logic-related procedure.

To group the indicators, various approaches from the field of multi criteria decision analysis (MCDA) have been investigated. The application of the RCIs coupled with MCDA methods is a process with a high degree of subjectivity. The involved user is asked to give his opinion along the process, involving his/her particular background, interests, personality, etc. This excess of subjectivity injected into the methodology is to be avoided, especially when various stakeholders could be involved, and each of them possibly giving a different judgment.

One possibility to do this has been found in the application of the PSA techniques in the context of decision making. Even if some limitations of such an application exist (limitations due to the simulation software, results to be judged in relative view), as highlighted in the publication added in Part IV, Chapter II, publication III, the approach has been successfully validated and positively accepted by external reviewers. After submission of (Colli et al., 2008b) to Safety Science international journal, the review, received by email

on 3 July 2008, has shown a positive acceptance. In particular, the second unknown reviewer wrote:
"*Reviewer #2: The paper presents a highly important and promising attempt to suggest a comparative methodology to rank and compare energy-related risks. The method, based on a set of RCIs, has its core and innovative aspects in the grouping and ranking procedure, which relies on a PRA-based logic-related process to obtain the final results. This is a new word in risk management in general, and energy-related risks in particular.*
The paper has no real weaknesses, besides the limitation indicated in the study by the authors, namely that the overall methodology requires a further uncertainty investigation. Should the authors be successful in achieving this, they must definitely compile another article and preferably submit it for publication in Safety Science."

9.1.3. The extended use of PSA in new energy systems.

As this thesis has partly demonstrated, PSA is a quite versatile technique. Its enlarged use in various energy sectors could definitely help both in planning and in scheduling maintenance procedures for a certain installation. PSA is for sure an added value for knowing more in details the weaknesses of the process under analysis, and consequently implementing the related parts.
Nevertheless, problems can be encountered when facing the data and information availability for building models. This issue has been met also during the development of the photovoltaic manufacture industry model and study, forcing to introduce various assumptions.
Another additional problem related to the use of PSA is the expertise level of involved people. The method requires specific knowledge and appropriate trainings.

9.2. Internal validation and limits of the methodology.

The proposed methodology has been validated using the available resources. Concerning the part of the method based on the RCIs, the validation has been done first checking the convergence of the PSA-like grouping model, and secondly applying few accidental events from three fossil fuel chains, whose results are shown in the paper added at the end of this book, in Part IV, Chapter II, publication III.
From the point of view of the application of PSA techniques in the context of new energy systems, the first PSA study for the multi-crystalline silicon photovoltaic cells manufacture industry has been performed, and the main results obtained are discussed in the last paper included at the end of the thesis, Part IV, Chapter II, publication IV.
In both publications, the results obtained confirm the validity of the work done. The issues connected to those practical applications arise mainly from:

1. For the application of the RCIs, limitations have been encountered coming from the limited amount of data available for the purpose of comparison, including missing data about probabilities and about uncertainty of the initial data. For this reason, assumptions have been introduced. Subjective probabilities for the indicators involved in the validation process have been used, and the uncertainty of the input information has been evaluated. The limitations of this application are mainly associated to the use of the PSA simulation program in a context with high probability values, as discussed in details in the publication III (Colli et al.,

2008b). Moreover, the results must be read in a relative view, and not as absolute values.

2. For the photovoltaic-related PSA study, the main limitations come from the lack of open availability of data from the PV industry for use in the model. Various reasonable assumptions have been introduced. Anyhow, also in this case, the results have been satisfying and highlighted various weak links in the manufacture process under analysis.

In both the previous practical applications, the results could be validated on the backbone of the existing reference literature in the related fields.

9.3. External acceptance of the methodology.

The work performed has been accepted by the scientific community. Evidences are the published papers and the positive comments received, as shown in the previous Section 9.1.2.

The methodology itself has proven to be reliable in the obtained results.

The only issue which is still open is the acceptance by the energy industry, where users may be focused on their private interests and not easily accept the methodology proposed. Especially when proposing new approaches, scepticism is high as long as the results are not seen as reliable and in accordance with specific interests.

The problem can be considered partly an interest-related problem, and partly a knowledge-related problem. It must be said that PSA techniques are not so easily understandable, and thus not straightforwardly accepted, by non experts. Even if PSA is based on the concepts of Boolean logic, this is not an immediate approach for everyone.

Concerning interest-related issues, discussions could arise immediately from the set of proposed RCIs. For some energy fields, especially where the wide view among various energy systems is missing and more specific interests are dominant, they could be seen as not totally appropriate. In fact, some indicators have been developed with specific focus, for example, on the nuclear chain, where radiological effects are relevant and need to be specifically targeted.

In such a situation it must be stressed that the tool proposed can be easily adapted to specific interests just 'switching off' the unwanted indicators from the involved fault trees of the model. If this is not enough, new indicators could be added to satisfy the specific interests.

Thus, looking to the methodology from a different angle, it can be seen as a tool to build tools. It is the theoretical path followed which is really the added value offered by this work. Adaptability is not an issue. Acceptability requires still some effort, from the scientific part to propose the method, and from the user to understand it.

9.4. Future work.

Reaching the conclusions of this thesis, it is clear that the general rule for the methodology proposed is set. Anyhow, additional details could be added and deeper investigation could be carried on in the future.

Three main areas of possible future development and implementation of the existing methodology can be identified:

1. Since the first pages of this thesis (see Chapter 1) the interconnection between risk and sustainability issues has been highlighted to enhance the present investigation.

The RCIs should be followed, to complete and complement the panoramic across the different aspects of the energy technologies, by a set of sustainability indicators (see, for example, (IAEA et al., 2005)), which should cover the positive aspects, in terms of the benefits brought from the energy systems to the environmental, social, and economical dimensions. The idea to create a connection between risk and sustainability aspects is clearly discussed in (Gray, Wiedemann, 1999). To achieve the combination of risk and sustainability aspects, a causal structure specific for sustainability should be developed, including a new set of indicators: the sustainability characterisation indicators (SCIs). Then, such a structure could easily follow the same PSA-based grouping modelling approach used for the RCIs. Risk and sustainability are two different concepts, but they also have an overlapping zone in common, meaning that some aspects are in common to both areas. Given this fact, the models for risk and sustainability shouldn't be two stand-alone models working in parallel, but they should be merged to work together. Even if this issue definitely needs further investigation, it already appears feasible to include the input coming from the risk-related set into the sustainability-related one, to reach an overall evaluation. The possibility to do this exists within the PSA modelling approach. What must be defined in advance is the 'why' and 'what', meaning that it must be clear in the mind of the user why he wants to do such a combination and what he wants to achieve. This is important to translate the desired needs into logic functions and to understand exactly what input from risk should be inserted and at which stage of the model. This obviously, requires a certain skill in PSA modelling.

2. During the uncertainty discussion, relevance has been put also on the evaluation of the uncertainty of the input data. In the presently hypothetic thought of the existence of a complete supporting database, on which the methodology discussed along this thesis can rely, then it would be important to quality all the information in use for comparison. One possibility could be the application of the Numeral Unit Spread Assessment Pedigree (NUSAP) method proposed in (Funtowicz, Ravetz, 1990). This technique is relevant in the identification and qualification of the background of the input data. The qualification of this information according to some relevant criteria could be good in defining the level of uncertainty associated to the input data. In fact, NUSAP uses both pedigree and uncertainty matrices. For more information and examples of application see http://www.nusap.net/.

3. One type of uncertainty which has not been addressed in this thesis, but which has quite a degree of importance and which it would be interesting to discuss and to see its effects on the results of the model, is the uncertainty of the user. To evaluate this topic, appropriate weighting factors could be introduced in strategic point along the steps of the process, to evaluate the results according to the optimistic/normal/pessimistic attitude of the user in specific energy risk matters. This approach will offer the possibility to understand the variations in the final ranking of the events according to the specific personality of the user, defining a range of variation. Such an approach, involving several simulations with different attitudes weighting factors, will practically lead the method to evaluate itself.

Obviously, as author of this work, my main hope is to see this methodology accepted and applied. It has been seen, evaluating existing methodologies, that this approach could be considered competitive in the in the field of decision making.
Once a large amount of data and information could be available to support the tool, the comparison of single events and pieces of information can be completed with views on the general trends about risk in different energy systems, achieving the final goal to which this methodology wanted to aim.

9.5. References.

(Colli et al., 2008a) - A. Colli, A.L. Vetere Arellano, C. Kirchsteiger, B.J.M. Ale, "Risk characterisation indicators for risk comparison in the energy sector", Safety Science, 47 (1), pp. 59-77, Elsevier, Jan 2009, http://dx.doi.org/10.1016/j.ssci.2008.01.005

(Colli et al., 2008b) - A. Colli, D. Serbanescu, B.J.M. Ale, “Indicators to Compare Risk Expressions, Grouping, and Relative Ranking of Risk for Energy Systems: Application with Some Accidental Events from Fossil Fuels”, Safety Science, 47 (5), pp. 591-607, Elsevier, May 2009, http://dx.doi.org/10.1016/j.ssci.2008.07.022

(Funtowicz, Ravetz, 1990) - S.O. Funtowicz and J.R. Ravetz, “Uncertainty and Quality in Science for Policy”, Kluwer Academic Publishers, (1990).

(Gray, Wiedemann, 1999) - P.C.R. Gray, P.M. Wiedemann, “Risk Management and Sustainable Development: Mutual Lessons from Approaches to the Use of Indicators”, Journal of Risk Research 2 (3), (1999), pp. 201-218.

(IAEA et al., 2005) - International Atomic Energy Agency, UN Department of Economic and Social Affairs, International Energy Agency, Eurostat and European Environment Agency “Energy Indicators for Sustainable Development: Guidelines and Methodologies”, IAEA, Vienna, (2005), http://www-pub.iaea.org/MTCD/publications/PDF/Pub1222_web.pdf

Summary

A Methodology to Allow Comparison among Different Energy Systems

Given the vast amount, in number and typology, of risk expressions coming from the energy environment, the possibility to compare among different energy systems is difficult. Taken the diversity of the various scenarios into account, the presented work proposes a methodology to overcome diversity of risk expressions and allow comparison among different energy systems, being them connected to traditional or innovative technologies.

The work is divided into four main stages. First, the investigation of ten different energy chains along their steps has led to the development of a common frame applicable to all fuel and life cycles. This initial analysis has also defined the most dominant risk scenarios associated to each step of the considered energy chains.
Second, a set of seventeen risk characterisation indicators (RCIs) has been developed on the backbone of the causal structure for hazard progression in an energy system. The RCIs have been tailored to serve the main characteristics of risk in the most convenient general form that makes the majority of them applicable to all energy systems.
Third, an innovative approach for grouping the indicators, and ranking the events to which they are applied, is used, based on the concepts of Boolean logic applied in the form of event and fault trees. This application, based on the mathematical meaning of the probabilistic safety assessment (PSA) technique, has been proven to be satisfactory, leading to the limitation of the subjectivity injection in the grouping and ranking procedure in comparison with the usually adopted multi-criteria decision analysis (MCDA) methods.
The uncertainty analysis on the performed numerical application of the described methodology has identified in the input data the major source of uncertainty, while the method itself has an acceptable level of uncertainty that makes it reliable for information processing.
Last, the conclusive part has covered the problem of missing consistent risk expressions and information concerning new energy systems adopting new technologies. As the aim of the work is to allow comparison among different energy systems, it is important not only to include traditional energy systems, but also the innovative ones just approaching the market. Again, the method proposed relies on the use of PSA. The first PSA study developed on a manufacture line for multi-crystalline silicon photovoltaic cells has been performed. Due to lack of specific data from the photovoltaic sector, only a general approach could have been performed, but sufficiently reliable to obtain results in line with the main safety studies in the sector. Moreover, the model is ready for further implementation and could be easily adapted to a real case. Though having the results from a PSA study, the possibility to compare them with possible results coming from the application of RCIs requires a further step involving the transformation of numerical results from both sides into a verbal ranking (such as high, medium, low ranking categories) which makes them comparable. This requires the involvement of expert judgment, in addition to the consideration of the specific criteria leading to the assignment of a specific risk level.

The proposed methodological approach is promising. It can be easily adapted to various needs, it could be also used with a different set of indicators, and so far it has received a quite positive evaluation by the scientific community. Anyhow, in parallel to the benefits that this methodology could bring, it is also very important to be aware of its limitations, like, for example, the need to interpret the results in a relative view, and not as absolute values. Moreover, its practical application in a wide context of comparison among different energy systems would require the availability of a relevant amount of data which is hard to obtain. The acceptability of PSA techniques by sectors which are not used to it, together with the difficulties in communication of risk issues and concepts with non-experts, are also points which require particular effort.

Alessandra Colli
Bergen NH, March 2009

Propositions

Propositions belonging to the dissertation "A Methodology to Allow Comparison among Different Energy Systems", Alessandra Colli, 6 May 2009.

1. The perception of risk, driven by various interests, seems to be a powerful force in influencing risk-related activities. Risk connected to the energy sector can not be zero, but as long as various interests are connected to energy it will be far from zero.
2. With energy and technology diversification we can improve security of energy supply, but we also increase the number of possible hazards.
3. The complexity of risk needs investigations in various directions. But, ironically, more questions are rising: the more you know, the more you understand that there is so much that you do not know.
4. Risk and sustainability are complementary concepts and should both be considered in reaching an overall view of the impact of an energy system.
5. The probabilistic safety assessment (PSA) method has proven to be a versatile technique to evaluate complex systems in various energy fields.
6. PSA can be adapted to evaluate risks in more general complex systems, as a tool to support risk informed decision making.
7. The way data are collected should be always rigorous and accurate, to avoid systematic errors to enter in the evaluation process and affect the final results.
8. The method (PSA) is dominant for the results. However, it is equally important to be able to evaluate the results (Shannon entropy) when we are not sure of the input in the method.
9. When developing indicators we need to focus on specific interests, but the method to group them has general application. Practically, we need to combine deductive and inductive approaches in a general-particular-general sequence.
10. Redundancy and diversity are powerful tools to reduce entropy in energy-, information-, substance-related isolated systems.

These propositions are regarded as defendable, and have been approved as such by the supervisor, Prof. Dr. B.J.M. Ale.

Stellingen

Stellingen behorend bij het proefschrift “A Methodology to Allow Comparison among Different Energy Systems”, Alessandra Colli, 6 mei 2009.

1. De waarneming van risico, die door diverse belangen wordt gedreven, schijnt een sterke kracht te zijn in het beïnvloeden van op risico betrekking hebbende activiteiten. Risico verbonden aan de energiesector kan niet nul zijn, maar zolang diverse belangen aan energie verbonden zijn, zal het verre van nul zijn.
2. Met diversificatie van energie en technologie kunnen wij de zekerheid van energievoorziening verbeteren, maar we verhogen ook het aantal mogelijke gevaren.
3. De complexiteit van risico vergt onderzoek in diverse richtingen. Maar ironisch genoeg, neemt het aantal vragen toe: hoe meer we weten, hoe meer we begrijpen dat er zoveel meer is dat we niet weten.
4. Risico en duurzaamheid zijn elkaar aanvullende concepten en zouden allebei moeten worden overwogen bij het vormen van een algemeen oordeel over het effect van een energiesysteem.
5. De probabilistische veiligheidsanalyse (PSA) is een veelzijdige techniek gebleken voor de evaluatie van complexe systemen in verschillende energiegebieden.
6. PSA kan worden aangepast om risico's in meer algemene complexe systemen te evalueren, als hulpmiddel om risico-geïnformeerde besluitvorming te ondersteunen.
7. De manier waarop gegevens worden verzameld zou altijd streng en nauwkeurig moeten zijn om te vermijden dat systematische fouten in het evaluatieproces terecht komen en de uiteindelijke resultaten beïnvloeden.
8. De methode (PSA) is dominant voor de resultaten. Het is echter even zo belangrijk de resultaten (Shannon entropie) te kunnen evalueren wanneer we niet zeker zijn van de input in de methode.
9. In het ontwikkelen van indicatoren moeten we ons op specifieke belangen concentreren, maar de methode om ze te groeperen heeft algemene toepassing. Praktisch gezien moeten we deductieve en inductieve benaderingen combineren in een algemeen-specifiek-algemeen opeenvolging.
10. Redundantie en diversiteit zijn krachtige hulpmiddelen om entropie te verminderen in energie, informatie en substantie gerelateerde geïsoleerde systemen.

Deze stellingen worden opponeerbaar en verdedigbaar geacht en zijn als zodanig goedgekeurd door de promotor, Prof. Dr. B.J.M. Ale.

Curriculum vitae

Alessandra Colli

Date of birth: 11 September 1972
Place of birth: Verona, Italy

1986-1991:	Liceo classico Scipione Maffei, Verona, Italy. High school (gymnasium and lyceum) with emphasis on the humanities.
1991-2002:	Politecnico di Milano, Milano, Italy. 5-year degree in electrical engineering. Graduation date: 20 December, 2002. Degree-thesis about wind energy and the impact of a wind farm on high voltage networks.
2003:	Joint Research Centre, Renewable Energies Unit, Ispra, Italy. Training on building integration of photovoltaic energy.
2003-2009:	Joint Research Centre, Institute for Energy, Petten, The Netherlands. Development of the Ph.D. work in cooperation with Delft University of Technology and additional tasks in the field of energy risk analysis.
From June 2009:	Scandpower Risk Management Inc., Houston, Texas, US. Consultant for risk and reliability analysis services with emphasis on the nuclear services market.

Certified training courses:

- Introductory course to ESP-r held on 8-9 September 2005 at the Energy Systems Research Unit (ESRU) of the University of Strathclyde, Glasgow, UK.
- Power system analysis with NEPLAN, held on 1-3 October 2007 by Luigi Busarello (from BCP Busarello + Cott + Partner AG, Erlenbach, Switzerland) at the Joint Research Centre, Institute for Energy, Petten, The Netherlands.
- Risk Spectrum PSA Professional software for Probabilistic Safety Analysis (PSA) and PSA Level 2, held on 3-7 December 2007 by the risk management company Relcon Scandpower AB in Stockholm, Sweden.
- "Industrial Safety: Risk Evaluation Techniques", University of Engineering Politecnico di Milano, Energy Department, 3-6 March 2008, Milan, Italy.
- "Internal Auditor ISO 9001:2000", held on 3-4 July 2008 by BSI at the Joint Research Centre, Institute for Energy, Petten, The Netherlands.
- "Advanced methods for reliability and availability analysis of industrial systems and plants", University of Engineering Politecnico di Milano, Energy Department, 15-18 September 2008, Milan, Italy.

Contact: alessandra.colli@gmail.com

PART IV

Publications

I. List of publications.

1. J.J. Bloem, A. Colli, "Simplified Energy Performance Calculation Method and Economical Analysis of BIPV Systems", PV-Hybrid and Mini-Grid, OTTI Energie-Kolleg, 25-26 September 2003, Kassel (Germany).
2. J.J. Bloem, A. Colli, "Effect of incentive schemes on integration of photovoltaics in the residential built environment", Energy Efficiency in Domestic Appliances and Lighting (EEDAL) Conference, 1-3 October 2003, Turin (Italy).
3. J.J. Bloem, A. Colli, P. Strachan, "Evaluation of PV Technology Implementation in the Building Sector", key-note speech at the Passive and Low Energy Cooling for the Built Environment (PALENC) Conference, 19-21 May 2005, Santorini (Greece).
4. J.J. Bloem, A. Jaeger-Waldau, A. Colli, "Economic Analysis of Photovoltaic Shading Devices in the Mediterranean Built Environment", 20th European Photovoltaic Solar Energy Conference and Exhibition, 6-10 June 2005, Barcelona (Spain).
5. C. Kirchsteiger, A. Colli, "Comparison of Energy Risks and Development of an Energy Risks Monitoring (ERMON) System - A JRC Research and Development Project", SAFERELNET Newsletter, Issue 5, May 2004, ART 91971.
6. A. Colli, C. Kirchsteiger, "Analysis of Reported Risk Figures for Natural Gas Transmission Pipelines. Safety & Regulatory Aspects", European Commission, JRC Report EUR 21308 EN, Petten, August 2004.
7. A. Colli, A.L. Vetere Arellano, C. Kirchsteiger, "Development of a General Scheme for Fuel Cycles and Life Cycles from all Energy Technologies as a Basis for the European Energy Risk Monitor (ERMON)", European Commission, JRC Report EUR 21735 EN, Petten, May 2005.
8. A. Colli, C. Kirchsteiger, B.J.M. Ale, "Comparison of Energy Risks and Development of an Energy Risk Monitoring (ERMON) System", peer reviewed publication for the PhD Student Symposium, 30 August 2005, Delft, Netherlands.
9. A. Colli, C. Kirchsteiger, A.L. Vetere Arellano, B.J.M. Ale, "Methodology Based on Indicators for Comparison of Risks Results from Different Energy Systems", peer reviewed publication for the Annual Conference of the Society for Risk Analysis – Europe 2005, Major Risks Challenging Publics, Scientists and Governments, 12-14 September 2005, Politecnico di Milano-Polo di Como, Como, Italy.
10. A. Colli, C. Kirchsteiger, A.L. Vetere Arellano, B.J.M. Ale, "Methodology for the Comparison of Risk Assessment Results from Different Energy Systems", key-note speech at the 2nd International Congress Sustainable Management in Action (SMIA), 19-20 September 2005, University of Geneva.
11. C. Kirchsteiger, A.L. Vetere Arellano, A. Colli, "Safety and Security of Energy Infrastructures in a Comparative View", 29th ESReDA Seminar, 25-26 October 2005, Ispra, Italy.
12. A.L. Vetere Arellano, A. Colli, C. Kirchsteiger, "Towards Consistent Comparative Energy Risk Assessment: the ERMON Project", 3rd International Symposium on

Systems and Human Science, Complex Systems Appraches for Safety, Security, and Reliability (SSR2006), 6-8 March 2006, Vienna, Austria.
13. C. Kirchsteiger, A.L. Vetere Arellano, A. Colli, "Comparative Risk Assessment for Different Energy Infrastructures - The European Commission's Energy Risks Monitor (ERMON)", peer reviewed publication for the Safety and Reliability International Conference (ESREL), 18-22 September 2006, Estoril, Portugal.
14. V.M. Fthenakis, A. Colli, A.L. Vetere Arellano, C. Kirchsteiger, B.J.M. Ale, "Evaluation of Risks in the Life Cycle of Photovoltaics in a Comparative Context", 21st European Photovoltaic Solar Energy Conference and Exhibition, 4-8 September 2006, Dresden, Germany.
15. A. Colli, C. Kirchsteiger, B.J.M. Ale, "The Energy Risk Monitoring (ERMON) System – Progress and Problems", peer reviewed publication for the PhD Student Symposium, 24 October 2006, Delft, Netherlands.
16. C. Kirchsteiger, A.L. Vetere Arellano, A. Colli, "Towards a European Energy Risks Monitor to Consistently Map Safety and Security Risks of Different Energy Infrastructures", Safety Science, 45 (9), p.905-919, Elsevier, Nov 2007, http://dx.doi.org/10.1016/j.ssci.2006.12.002
17. A. Colli, A.L. Vetere Arellano, C. Kirchsteiger, B.J.M. Ale, "Risk Characterisation Indicators for Risk Comparison in the Energy Sector", Safety Science, 47 (1), pp. 59-77, Elsevier, Jan 2009, http://dx.doi.org/10.1016/j.ssci.2008.01.005
18. A. Colli, D. Serbanescu, B.J.M. Ale, "PRA-Type Study Adapted to the Multi-crystalline Silicon Photovoltaic Cells Manufacture Process", in "Safety, Reliability and Risk Analysis: Theory, Methods and Applications", Martorell et al. (Eds.), Taylor & Francis Group, London, ISBN 978-0-415-48513-5, for ESREL 2008 & 17th SRA Europe Annual Conference, 22-25 September 2008, Valencia, Spain.
19. D. Serbanescu, A. Colli, A.L. Vetere Arellano, "On some aspects related to the use of integrated risk analyses for the decision making process, including its use in the non-nuclear applications", in "Safety, Reliability and Risk Analysis: Theory, Methods and Applications", Martorell et al. (Eds.), Taylor & Francis Group, London, ISBN 978-0-415-48513-5, for ESREL 2008 & 17th SRA Europe Annual Conference, 22-25 September 2008, Valencia, Spain.
20. A. Colli, D. Serbanescu, B.J.M. Ale, "Indicators to Compare Risk Expressions, Grouping, and Relative Ranking of Risk for Energy Systems: Application with Some Accidental Events from Fossil Fuels", Safety Science, 47 (5), pp. 591-607, Elsevier, May 2009, http://dx.doi.org/10.1016/j.ssci.2008.07.022
21. Journal submission under review: A. Colli, D. Serbanescu, B.J.M. Ale, "PSA-Type Analysis for the Multi-crystalline Silicon Photovoltaic Cells Manufacture Process", Risk Analysis, 2008, Manuscript No. RA-00240-2008.

II. Relevant publications.

I. C. Kirchsteiger, A.L. Vetere Arellano, A. Colli, "Towards a European Energy Risks Monitor to Consistently Map Safety and Security Risks of Different Energy Infrastructures", Safety Science, 45 (9), p.905-919, Elsevier, Nov 2007, http://dx.doi.org/10.1016/j.ssci.2006.12.002

II. Colli, A.L. Vetere Arellano, C. Kirchsteiger, B.J.M. Ale, "Risk Characterisation Indicators for Risk Comparison in the Energy Sector", Safety Science, 47 (1), pp. 59-77, Elsevier, Jan 2009, http://dx.doi.org/10.1016/j.ssci.2008.01.005

III. Colli, D. Serbanescu, B.J.M. Ale, "Indicators to Compare Risk Expressions, Grouping, and Relative Ranking of Risk for Energy Systems: Application with Some Accidental Events from Fossil Fuels", Safety Science, 47 (5), pp. 591-607, Elsevier, May 2009, http://dx.doi.org/10.1016/j.ssci.2008.07.022

IV. Colli, D. Serbanescu, B.J.M. Ale, "PRA-Type Study Adapted to the Multi-crystalline Silicon Photovoltaic Cells Manufacture Process", in "Safety, Reliability and Risk Analysis: Theory, Methods and Applications", Martorell et al. (Eds.), Taylor & Francis Group, London, ISBN 978-0-415-48513-5, for ESREL 2008 & 17th SRA Europe Annual Conference, 22-25 September 2008, Valencia, Spain.

Available online at www.sciencedirect.com
ScienceDirect
Safety Science 45 (2007) 905–919
SAFETY SCIENCE
www.elsevier.com/locate/ssci

Review

Towards a European energy risks monitor to consistently map safety and security risks of different energy infrastructures

Christian Kirchsteiger *, Ana Lisa Vetere Arellano, Alessandra Colli

European Commission, DG JRC, Institute for Energy, Westerduinweg 3, 1755 LE Petten, Netherlands

Received 23 March 2006; received in revised form 5 December 2006; accepted 15 December 2006

Abstract

After mapping of current European Union regulations on the management of accident risks related to natural hazards and different industrial activities, this paper discusses insights from past and current European Commission initiatives on harmonisation of assessment and management of safety risks. The problem of safety comparison and risk/benefit communication is of critical importance for sustainable decision making. For the specific case of the energy sector, the European Commission's Joint Research Centre (DG JRC) and DG TREN (Directorate General for Transport and Energy) have recently started two connected initiatives, called energy risks monitor (ERMON) and safety and security of energy infrastructures in a comparative view (SEIF-CV). While ERMON deals with the development of a methodology and corresponding web-based information system to cross-compare in a consistent way safety, risk and reliability performances of different energy systems (fossil, nuclear, renewables) across their specific fuel cycle chains, SEIF-CV creates a corresponding network of stakeholders in the energy sector as well as the necessary review and user panels for ERMON. Objectives and status of ERMON and SEIF-CV are described.

Keywords: Risk assessment; Comparative risk assessment; Risk communication; Decision support; Energy risks; Risk management; Risk governance

* Corresponding author. Tel.: +31 224565118.
E-mail address: christian.kirchsteiger@jrc.nl (C. Kirchsteiger).

0925-7535/$ - see front matter
doi:10.1016/j.ssci.2006.12.002

Contents

1. Background

1.1. Need for consistency in risk management

Technological progress is directed towards fulfilling human needs for development and progress. At the same time, the detriments or risks arising from specific technologies cannot be avoided. The potential public health, environmental and economic risk impact of technologies is therefore a topic of considerable public and professional debate across all different industry sectors – from energy production to transport and process industries. This demonstrates the need for all different types of risks to be systematically assessed and managed in order to protect public health and safety, and to limit the environmental and economic impacts of potential accidents.

Risk-informed methods provide various qualitative and quantitative measures that can significantly support consistent decision-making on managing accident risks related to a specific technology across its entire life cycle.

However, these methods rarely consider the requirements of individuals who may find themselves in need of information on the ‘‘risk dimension’’ of a certain technology compared to alternatives with similar benefits. Therefore, there is a necessity for risk assessment methods and modelling data to be consistent within a specific technology sector or across technological divides so that they can produce results that are, at least in principle, dependable and comparable.

An additional challenge is posed by the recent international trend to focus on security related risks (intended hazards, i.e. malicious acts) rather than safety risks (unintended hazards, due to natural or technological causes). Although it is repeatedly mentioned that research is needed on the new security challenges (COM(2004)72 – http://europa.eu.int/

eur-lex/en/com/cnc/2004/com2004_0072en01.pdf; Research for a secure world – http://europa.eu.int/comm/enterprise/security/doc/gop_en.pdf), which contain the dual elements of security and safety, there is little common understanding on the practicalities of the issue. As an example, there is currently no agreement on the extent to which external hazards (such as natural hazards, e.g. severe seismic events or floods) and security related events (such as terrorist attacks on a major hazardous installation) should be taken into account in defining emergency plans and emergency planning zones (Vetere Arellano et al., 2005).

1.2. Current EU regulations on technological risk management

The European Union (EU) currently has 25 Member States, 10 of which joined in 2004. The EU has many features of an actual federal system: It has an elected parliament, a European Court of Justice, and an executive, the European Commission (EC). There is an extensive body of EU legislation (e.g. "Directives") that takes precedence over national and regional laws. Through the Single European Union Act of 1987, hundreds of economic policies and regulations were "harmonised" to achieve the cross-national consistency necessary for the establishment of a true single European market.

Recent years have seen the manifestation of various kinds of risks, such as natural disasters, manmade disasters, criminal risks, terrorism risks, long term risks (e.g. pollution, climate change) and economic incidents. In many cases, the various kinds of damages or possibility of damages resulting from these events can give rise to difficulties in activities of an organisation or of a population, sometimes even affecting the organisation's or population's existence.

Against this background, the EC has taken in the last 10–20 years a number of legislative steps in order to protect safety, health and environment in the EU against both technological and natural hazards, e.g.,

- For natural hazards:
  – 2000 Water Framework Directive (http://europa.eu.int/eur-lex/pri/en/oj/dat/2000/l_327/l_32720001222en00010072.pdf);
  – 2004 Regulation on Forest Fire Prevention (http://europa.eu.int/eur-lex/pri/en/oj/dat/2003/l_324/l_32420031211en00010008.pdf);
  – 2004 Floods Communication (http://europa.eu.int/eur-lex/en/com/cnc/2004/com2004_0472en01.pdf);
  – 2006 Proposal for a Directive on assessment and management of floods (http://europa.eu.int/comm/environment/water/flood_risk/pdf/com_2006_15_en.pdf), etc.
- For technological hazards:
  – 1982–1996 Directive on Control of Major-Accident Hazards Involving Dangerous Substances ("Seveso Directive", http://europa.eu.int/comm/environment/seveso/index.htm);
  – 2003 Proposed Maritime Safety Directive (http://europa.eu.int/eur-lex/lex/LexUriServ/site/en/com/2003/com2003_0001en01.pdf);
  – 2004 Railway Safety Directive (http://europa.eu.int/eur-ex/lex/LexUriServ/site/en/oj/2004/l_220/l_22020040621en00580060.pdf);

– 2002–2004 Draft Directive on the Safety of Nuclear Installations (http://europa.eu.int/comm/energy/nuclear/safety/doc/com2003_0032en01.pdf), etc.

In addition, the integrated EU Civil Protection mechanism as well as the ECs INSPIRE and GMES initiatives ensure a proper integral treatment of natural and technological hazards (see: http://ec.europa.eu/environment/geo).

EU Safety Directives define generic objectives, but leave – with a very few exceptions – the development and application of scientific/technical methods, data and acceptance criteria to the EU Member States (subsidiarity principle). When implementing a Directive into national law, Member States are free to adopt specific measures to pursue its mandatory overall objectives and to judge how this is practically ensured. However, as diversity of specific technical approaches (methods, criteria) and traditional safety philosophies is kept on the national level, a need for some level of EU-wide harmonisation arises in order to make estimated risk levels comparable, and thus to ensure similar levels of protection for people and the environment as well as fair treatment of transnational enterprises throughout the EU. Usually, the problem is not one of compliance, but of transnational approaches – and, in the case of safety/security issues, also more and more a problem of proper risk communication. This is also the reason why in a more and more interconnected Europe and globalising world there is a need for improving dialogue and trust between the stakeholders involved (e.g. regulatory authorities, industry, consumers, other social partners, non-governmental organisations, etc.).

1.3. The specific case of the energy sector

The use of different systems for the generation and distribution of energy, such as different fossil energy carriers, is at the base of any advanced society. They provide the basic resources for industrial production, transport and domestic needs. On the other hand, they involve hazardous activities that pose a threat to public health and environment and create problems in dealing with dangerous wastes. During the last years a lot of attention has been paid by regulators, utilities, environmental groups and the general public in Europe and worldwide to risk issues related to the use of the different types of energy systems across their fuel cycle chains.

The current socio-economic system is largely based on centralized conventional energy sources (fossil, nuclear) and their distribution systems. In addition, legislation and the liberalization of the energy market are focused on helping new or improved energy technologies to join the market at a competitive level, offering more possibilities for distributed generation. Examples mentioned in the EU 2000 Green Paper "Towards a European Strategy for the Security of Energy Supply" (http://europa.eu.int/eur-lex/en/com/gpr/2000/act769en01/com2000_0769en01-01) and the recent update/commentary on it (http://europa.eu.int/comm/energy_transport/en/lpi_lv_en1.html) to counter the increasing energy supply dependence of the EU are renewable energy as well as advanced nuclear technologies to help to reduce dependence on imports and increase the security of supply and at the same time limit the greenhouse gas emissions, in support of the Kyoto protocol.

In such a wide context, where safety assessment practices and criteria are often incomplete and inconsistent, the problem of safety comparison and risk/benefit communication is of critical importance for sustainable decision making in the energy sector.

2. Towards more harmonisation in risk management on a European level

Harmonisation of risk assessment methods, data and acceptance criteria is a traditional activity of the ECs Directorate General Joint Research Centre (DG JRC). The mission of the JRC is to provide customer-driven scientific and technical support for the conception, development, implementation and monitoring of EU policies. As a service of the EC, the JRC functions as a reference centre of science and technology for the EU.

In May 2000, the JRCs Nuclear Safety and Systems Modelling and Assessment Units organised a large International Workshop to review the status of technological risk assessment across different industry sectors (nuclear and non-nuclear power industry, chemical process industry, waste treatment facilities, various transport sectors, food industry, medical devices) (Kirchsteiger ed., 2002).

Throughout the workshop's presentations and discussions of risk assessment practices across different industries and countries, it became clear that there are many similarities in risk assessment at a generic technical level. The process of risk-informed decision making can be broken down into a few basic steps, a sequence which could – although there are differences in terminology – widely be accepted across industries. However, the fulfilment of each step is heavily dependent on the specific cultural and regulatory context. Most workshop participants agreed that comparative risk assessment along harmonised procedures could significantly help the understanding of decisions made in other countries or sectors and promote a transparent decision making process in which all stakeholders can be involved.

It was generally felt that any successful standardisation should focus on the process underlying risk assessment, and not attempt to harmonise risk criteria. On the other hand, it should not be restricted solely to technical elements of risk assessment, but cover in some way also aspects of risk management and thus of decision making. Standardisation should not prescribe a particular risk assessment approach. The main objective of any such effort should be to help stakeholders see more clearly the range of possibilities and assist decision makers in decisions, which only they can make. For this reason, it was felt that a "universal risk assessment standard" is neither desirable nor realistic with regard to its wide acceptance and use, but that rather a "template", which maps out the technical steps in risk assessment in a generic way, should be considered for development.

This template should:

- Focus on technical aspects involved in risk assessment, e.g. by explaining what is meant with a certain term in a certain risk assessment context.
- Include generic components of decision making, e.g. by showing which are the common elements in making decisions, however not attempt to lay down what "tolerable" levels of risk might be.
- Avoid the duplication of efforts already done, and build on existing formal standards.

It is interesting to compare these conclusions and recommendations from 2000 with the much more recent ones (2006) from the Joint Expert Group "Critical Infrastructure – Energy Supply" by CEN, the European Committee for Standardisation.

JRC works together with CEN (http://www.cenorm.be) which has working groups dealing with development of standards and standard-like methods in many areas, incl. safety and security of energy infrastructures. CEN created in December 2003 the CEN

Technical Board (BT) Working Group (WG) 161 on "Protection and Security of the Citizen" as a monitoring and coordination platform for stakeholders. The goals of the CEN BT WG 161 include:

- Ensure coordination of standardisation activities in this area, notably with ISO.
- Assess the needs of all relevant stakeholders for security standards.
- Propose new standardisation activities as and where necessary.
- Recommend actions to be taken by the CEN BT on subjects within the field of security that may benefit from the development of standards.
- Ensure the CEN response to queries from stakeholders, in particular the EC services.

CEN BT/WG 161 focuses on needs for standards, standard-like documents, procedures, minimal codes of practice and similar recommendations, and review existing ones as necessary, in order to develop, harmonise, update or validate said documents. A number of expert groups have been established within CEN/BT/WG 161, incl. the mentioned Expert group "Critical Infrastructure – Energy Supply".

In the minutes of the most recent meeting of this group (June 2006), the following conclusions/recommendations are included (Sellerholm, 2006):

- The Subgroup on Oil and Gas performed a questionnaire survey among different industrial and governmental institutions in Europe; none of the responses expressed a need for a standard on risk assessment, however a generic guideline (template) on risk assessment methodology was proposed by several ones.
- Much more information on energy related incidents/accidents is needed in a readily available form and it was taken note of the fact that JRC is currently building a database on such events ("ERMON"; see Section 3).
- A platform for stakeholders on energy risks is needed, i.e. a platform for private–public dialogue and exchange of experiences, e.g. in the form of targeted workshops/conferences (such as "SEIF-CV"; see Section 4) or in the form of web-based information systems and platforms ("ERMON"; see Section 3).

It seems that between 2000 and 2006 the issue of harmonisation of technological risk assessment and risk management has been taken up at a European level, incl. strong participation of industrial partners and standardisation bodies. The 2006 CEN WG recommendation to move towards harmonised mapping of different risk assessment results (generated by different risk assessment methods/approaches/criteria) and harmonised communication of the findings via appropriate virtual or other platforms to all relevant stakeholders corresponds very much to the 2000 findings of the mentioned JRC workshop.

Following the 2000 workshop, the JRC has undertaken quite a large debate (internal to DG JRC as well as with other DGs of the EC and with Universities and Research Institutions of the EU Member States) in order to shape and define the content of the risk-related activities/projects under the 6th Framework Programme (FP6, 2003–2006; see e.g. http://www.cordis.lu/en/home.html). The problem of correctly assessing, managing and mitigating risk has gained importance and visibility in almost all fields of human activities, from GMOs to energy systems and transport activities. This visibility is reflected in the content of FP6, where risk is mentioned in many research areas, from the "classical" nuclear power plant risk assessments to food safety and natural hazards.

Within JRC, the Nuclear Safety Unit of JRCs Institute for Energy (JRC-IE) has an institutional activity dedicated to extracting generic principles, approaches, tools and methodologies from the large experience available from within the nuclear safety field for the development of a generic horizontal energy risk assessment platform. With the transfer of all nuclear safety activities from JRC Ispra to JRC Petten in 2001–2002 and the related transfer of competence in the risk assessment field, this work is performed by JRC-IE in the context of its energy risks monitor (ERMON) Project (see Section 3) in support of DG TREN, the Transport and Energy Directorate General of the EC. JRC-IE support to DG TREN includes assistance to ongoing working groups on harmonisation of specific energy safety issues, such as for natural gas pipelines safety.

Further, a major international conference on "safety and security of energy infrastructures in a comparative view" (SEIF-CV) has been organised by JRC together with DG TREN in November 2005 in Brussels with the aim to develop, on the basis of discussions among all stakeholders from different energy sectors recommendations for identifying and prioritising research as well as policy needs for Europe in order to secure its future energy supply. Further information is given in Section 4.

In addition to these European efforts, the International Risk Governance Council (IRGC) has established itself since a few years as an independent foundation that involves a public–private partnership which supports various sectors such as governments, business and other organisations in developing and developed countries (see: http://www.irgc.org). The IRGC creates value by offering a platform for global debate and as a source of compiled, and if possible unified, scientific knowledge on risk issues. Following its mission the IRGC also aims to foster public confidence in risk governance and in related decision-making by

- Reflecting different views and practices and providing independent, authoritative information.
- Improving the understanding and assessment of important risks issues and ambiguities involved.
- Designing innovative, efficient, and balanced governance strategies.

IRGC also elaborates generic recommendations and guidelines, which may, in the long run, develop into internationally accepted best-practice type of risk governance approaches.

3. The JRCs energy risks monitor (ERMON) project

3.1. Objective

In relation to the above-mentioned recommendations to establish a pan-European platform for all stakeholders on energy risks, JRC-IE started in 2004 the development of the so-called energy risks monitor (ERMON). The objective of ERMON is to offer tools for comparative assessment of accident risks of different energy systems, which allows any interested person or institution to compare "risk information" (e.g. risk assessment results, incident/accident statistics, statements on "the risk", etc.) from different sources/of different quality/in different formats related to the use of different energy systems across the various steps in their specific fuel/life cycle chains.

One basic problem when comparing risks associated to different energy systems is the large variety of available types of Risk Figures. Risk Figures (or risk expressions) may be either numerical or not and, within the numerical case, they may be based on actual historical data (accidents) or on prognostic studies (Probabilistic Safety Assessments, Best Estimate analysis and Worst Case Analysis among others). Further, these different Risk Figures usually have a very different background and underlying quality of information in terms of origin of data, type of model, quality assurance, peer review schemes, etc. This fact makes performance of comparisons difficult for non-experts and results not easy to communicate.

Within ERMON, a set of indicators is defined which are used to map the variety of available risk information into common metrics in order to allow results comparison, and to better understand the comparative risks and tradeoffs among different energy systems. This mapping is done in two phases (i.e. by using two different sets of connected indicators):

1. The first one ("risk characterisation") is related to the physical extent and perceived relevance of the possible risk of a particular hazard.
2. The second one ("risk qualification") 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 indicator mappings 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 different sources.

It is important to stress that the proposed project does not involve development of a new "European energy accident super-database", but aims at fully using the existing data resources from different European interest groups in a consistent manner. For this reason, involvement of data owners at an early stage is essential and is achieved by the specific composition of the project team.

3.2. Status and problems

During 2004–2005, the development of ERMON consisted of investigating the different available types of risk expressions (from risk assessments, reports, databases, etc.), and the steps along the energy chains for the different types of fuel (twelve chains considered – coal, natural gas, petroleum, nuclear, biomass, geothermal, hydro, solar, PV modules (life cycle), wind, wind turbines (life cycle), hydrogen).

The first activity resulted in the consistent identification of the most risk-prone step(s) along various energy fuel/life cycles, while the second one resulted in the development of a general scheme for all fuel/life cycles to be used as basis of comparison within ERMON (Colli and Kirchsteiger, 2005). This scheme is characterised by four main steps:

- production (related to all production operations);
- transportation (all transportation steps including raw material, waste, and storage);
- power generation (power plant, including construction and dismantling operations);
- waste treatment (waste from the power plant as well as from other production activities).

The development of such a general scheme, together with the identified energy systems into consideration, leads to the identification of a matrix $[A]$, consisting of elements a_{ij}, where i represents a step in the general fuel/life cycle and j represents a particular energy technology. Each element a_{ij} can then be related to a unique set of values from both the risk characterisation and the risk qualification indicators, as generated from the mapping of a piece of "risk information" (e.g. a risk assessment study). In this way, a consistent knowledge repository on the risks of different energy systems from different sources and different levels of completeness/detail etc. can be built up.

Regarding the risk characterisation indicators, a draft set has been constructed and is currently tested on different risk assessment results for different energy systems. The basic model is the set of twelve numerically quantifiable descriptors developed by Hohenemser et al. (2000) for technological hazards, a sequence of causally connected events leading from human needs and wants to the choice of the technology and further to the consequences caused by the release and the exposure to energy and/or material. The risk indicators will be applicable for the comparison of risk in the cases of normal operation, accident events and terrorist attacks. Consequences are evaluated in terms of human, environmental and economical effects.

To confirm the appropriateness of the risk characterisation indicators, an in-depth investigation is performed for three specific energy chains: natural gas for fossil technologies, solar photovoltaic for renewables and nuclear. The results for photovoltaic are close to publication.

The work on risk qualification indicators has not yet been started.

The overall model of ERMON is expected to be finalised in mid 2007 and the web-based information system ready for operation/use by end of 2007.

The project is part of the work program of JRC-IE and is performed by JRC-IE staff in cooperation with several external parties. Further collaborations with interested parties are welcome.

4. SEIF-CV process

4.1. Justification

ERMON is developed in parallel to the needs of DG JRCs Policy Customers at the EC. In the case of JRC-IE, this is mainly DG TREN. One measure to support DG TREN in their development and implementation of an EU policy for security of energy supply is JRCs organisation of conferences on safety and security of energy infrastructures in a comparative view (SEIF-CV). Safety and security aspects of energy infrastructures have come to the foreground recently, triggered by growing concerns about the reliability and continuity of energy supply as well as from enhanced attention to potential terrorism threats.

The first SEIF-CV Conference, held on 14–16 November 2005 in Brussels, was the spark of a process where dialogue and information exchange between the various stakeholders in the field of energy is promoted.

4.2. Objectives of conference

The aim and motivation of SEIF-CV is to present and discuss about pressures (safety and security risks, economical, socio-political, etc.) on the EU energy arena, and actions (standardised methods, research, policy measures, etc.) implemented to address this dynamic and interconnected landscape. The final aim is to identify and reach consensus from the different stakeholders (authorities, industry, NGOs, etc.) regarding important factors ensuring/threatening reliable supply of energy products for Europe for the different types of fuel, further needs for policy, research and standardisation on criteria and methods to ensure reliable supply, and how to improve risk communication at international level. The medium- to long-term vision is that if successful, SEIF-CV will be the launching of a series of Conferences/Seminars/Workshops on energy-related topics, in support to SEIF-CV partners' needs, particularly DG TREN.

SEIF-CV 2005, through multi-disciplinary and multi-sectorial actors involved in the energy field, compared the accident and security threats associated with various energy alternatives, from fossil fuels to renewables and nuclear. The event provided a forum for the ~200 participating scientists, industry, governmental authorities, NGOs, media and risk communication experts from Europe, USA, Japan and Russia to present their sector-specific energy risk experience, to promote mutual understanding of their respective roles, to share best practice and to develop informal recommendations for further European policy and research needs in support of DG TREN and DG RTD (the European Commission's Directorate-General for Research and Technological Development). In addition, the Conference also hosted a workshop on energy standards, dealing with three scenario based exercises to identify needs of future standardisation organised by CEN/BT Working Group 161 – Expert Group on Critical Infrastructure – Energy Supply.

The following sets of recommendations were developed in intensive discussions among the participants from industry, authorities, research, consultants and NGOs. Further information on SEIF-CV can be obtained from the authors or from http://www.energyrisks.jrc.nl.

4.3. Summaries of the discussion groups

The following sets of recommendations were developed in intensive discussions among the participants from industry, authorities, research, consultants and NGOs.

4.3.1. Policy roundtable recommendations

4.3.1.1. Safety issues.

(1) *Involving industries and other stakeholders in improving safety of energy infrastructures by identifying which issues can be harmonised at EU level, prioritising them and providing a method to address them (e.g. for pipelines):*
- There was general agreement that this would be useful, however, there is the need to respect the subsidiary principle and the need for a goal-setting approach, i.e. define goal, organise resources, implement actions to address goals, measure performance, review results and lessons learned to provide feedback to re-define goal, if required.

(2) *Moving towards a coordinated network of partners to create a Working Group on Accident Investigation and related issues:*
- Quality of investigations should be improved. Need for common method to ensure that when accident investigation is done, it is done at high quality. Lessons learned should be more easily detected and mainstreamed into future practice where responsibilities lie (individual and corporate). A Working Group on Acci-

dent Investigation at EU level could assist in ensuring high quality and endorse institutionalisation of procedures regarding lessons learned from accidents, guaranteeing feedback into preventive and mitigative risk management.

(3) *Life extension of structures and pipelines:*
- As there are many ageing infrastructures, there is a need for accepted tools to address ageing – need for a standard dealing with life extension of structures and pipelines on a risk-informed basis. Essential is common methodology for risk assessment geared to needs of infrastructure operators and based on information available to them from their systems. Learn from experiences in the nuclear field – importance of cross-sector sharing of good practice – there are many IAEA standards in this area.

4.3.1.2. Security issues.

(4) *Security issues should not overburden operators:*
- Industry has already done a lot on safety issues and has increased efforts on security issues. Operators may receive extra burdens from additional security requirements. This should not result in competition advantages between countries and/or energy sources. Thus, common guidelines and standards to give a level playing field are needed.
- Security measures should be kept at the local level as far as possible; extra measures should be based on proven methodologies, currently existing at company/Member State level.

(5) *Addressing the Subsidiary Principle with cross-border and burden-sharing issues:*
- Cross-border activities could be vulnerability assessment of interconnected systems (e.g. electrical grid, pipelines) and emergency management, which cannot be dealt with only at national level if several Member States are affected. In addition, cross-border contingency plans and interoperability of response measures need to be more widely developed.
- Methods to assess coordination at EU level could be useful to clarify the sharing of responsibilities between actors and also share potential burdens.

(6) *The EU Energy Strategy should NOT be solely conditioned by security issues:*
- The EU Energy Strategy should be a long-term vision that includes security issues to the extent of their importance relative to the other issues.
- There are language/concept problems that need to be addressed in a systematic manner. In some countries safety and security are distinct words (e.g. English [safety, security] and French [sûreté, sécurité]), whereas in many languages it is the same word (e.g. Italian [sicurezza], German [Sicherheit]). Thus, a common terminology needs to be defined.
- Need to exchange experiences to better understand the concept. At EU level, a framework could be useful to share concepts and promote security culture.

4.3.1.3. General issues.

(7) *Safety and security are generally addressed separately in policies, although they are interrelated concepts. However, there is a lack of a clear definition of the boundaries:*
- Need to address this issue in a systematic and participatory manner, as overlaps between safety and security due to lack of a clear and accepted boundary

definition could lead to inadequate allocation of resources. Safety issues are generally driven by the potential (or known) consequences of events on people and the environment while security issues are generally driven by the awareness of threats (malicious, natural, technological, political, etc.) and measures to mitigate against these threats. Interfaces between safety and security should be highlighted and potential conflicts eliminated, in order to have consistent control of potential consequences.

(8) *Confidentiality: obstacle (for safety) or necessity (for security)?*
  - Need to strike information exchange balance between meeting needs of owners/operators of energy infrastructures who do not wish to provide a "recipe to cause disaster" to terrorists, but ensuring that inter-sectoral dialogue and public involvement are not hindered, so that informed decisions can be made.
  - Need to ensure that confidential information has a systematic peer-review mechanism at an agreed level of access and that the security of this information is guaranteed. This would result in sustaining the quality of information and promoting inter-sectoral cooperation towards sustainable progress.

4.3.2. Research roundtable recommendations

4.3.2.1. Safety and security.

- Need to promote research towards establishing an energy security culture. Setting up training curricula could be one step towards achieving this (e.g. starting with nuclear security culture).
- Need to increase research efforts in mainstreaming risk-informed design by integrating safety and security issues already in design phase and by ensuring transparency (i.e. stakeholders should be engaged already in design phase, with opportunity to provide comments and feedback). Regarding nuclear, consensus was that this should also be linked to the Generation-IV Initiative on advanced reactor designs.
- Need to support cross-fertilisation of safety and security experiences across different energy sectors (especially nuclear versus other energy sectors) and to develop support tools for assisting with handling stress situations.
- Need to address vulnerabilities to attacks of information and control systems for energy infrastructure operation and the consequences seem not to be given the attention they deserve. Cyber-attacks are a steadily growing problem in general.
- Need for program of education and training as part of the Research–Innovation–Education/Training triangle.

4.3.2.2. Security of supply.

- Need to promote research and rules (policy?) for security of energy supply: Example of developing simple systems that are more insensitive systems towards disruptions ("bad quality but good supply").
- Need to further mainstream smart energy networks for integration of renewable sources and distributed generation in various economical sectors (electricity, transport, heating, etc.) with the push from research.
- Need to promote research with regard to a future hydrogen economy, incl. clean coal, CO_2 capture and storage, advanced nuclear systems (e.g. Generation IV) etc.
- Need to promote research in providing effective information feedback for energy policy-making, e.g. comparative assessment and risk communication.

- Need to improve knowledge and understanding of short- and long-term threats to energy supplies and transmission systems, incl. propagation of disruptions. System-wide models for simulation of disruptions (both real and hypothetical) are needed.
- Need to consider the external dimension of an EU energy security strategy.

4.3.2.3. Risk communication/acceptability.

- Need to strengthen the policy-maker/public interface through research support. It is essential that governments learn to know how to better communicate with the public. Training courses on risk communication could be promoted, incl. participation of more representatives from governmental authorities.
- Need to promote collaborative exercises amongst stakeholders, supported by targeted research, to ensure that efforts are optimised (e.g. transboundary nuclear emergency preparedness exercises).
- Need for wider understanding of financial and economic risks of systemic failures (e.g. a recent black-out in Austria lasted only a few hours but cost the country €40 million/h). Risks could be reduced by improved interconnections both nationally and across Member State borders.
- Need to ensure the continuity of energy-related FP6 (2003–2006) Technology Platforms in FP7 (2007-2013). These technology platforms promote multidisciplinary dialogue and cross-fertilisation of good practices across different technology sectors.
- Need to promote research in safety/security culture and human factors in order to better identify and understand boundary conditions of technological risk reduction capacity, for a given situation.
- Need to support research that analyses and proposes methodologies to better communicate risks, benefits, uncertainties and costs already at the design stage, e.g. exclusion of potential for very high consequences (i.e. if the very high consequence scenario would be considered, the cost of the structure needed to address this would be too expensive and such an over-design would be impractical when set against a background of prioritising resource allocation in an effective manner).

4.3.2.4. Comparative assessments.

- Need to better coordinate different research efforts at EU level in the area of energy risk assessment (i.e. safety, security and security of supply), communication to decision-makers and the public (mainly for comparative energy risk assessment, e.g. EU-funded projects ExternE, NEEDS, etc.). There are several research groups working on similar topics addressing the same users, thus over-laps and redundancies should be avoided.
- At present, there is no general EU-wide risk assessment and risk management framework across different technologies. Examples: Lack of balance in current risk acceptance criteria for the chemical process and nuclear industries. Very different levels of quality in risk assessments for different sectors (lack of "quality measures", cross-industry guidances etc.). There is a need to provide a peer-reviewed and user-driven methodology that addresses this issue to promote risk-informed decision-making for different stakeholders (policy-makers, operators, public).

4.3.3. Standardisation recommendations

In the frame of SEIF-CV, a scenario-based workshop on standardisation (organised by the CEN Expert Group on Critical Infrastructure – Energy Supply) attracted 40 participants to identify areas where standardisation could be required. This was done during the first day of the workshop. The second day was labelled a round table The following recommendations resulted from the workshop:

- There is a need for communication of the very meaning of standards and its "fitness for use" within the area of energy safety and security.
- In the following areas there is an obvious need for standardisation:
  - Terminology to enhance preconditions for good crisis management.
  - Common communication procedures for crisis management.
  - Common definition of impact categories for crisis management.
- Continued work within the CEN Expert Group Energy Supply to further specify the identified areas in need of standardisation based on the action areas: prevention, protection, crisis management, consequence management and lessons learned management.

Following the SEIF-CV Conference, the Expert Group on Critical Infrastructure – Energy Supply has continued its work using the output from the workshop as a basis for further elaborating the recommendations for future standardisation activities. Presently, three sub-groups are established; Electricity, Oil and Gas, and SCADA (Supervisory Control and Data Acquisition Systems). Each sub-group maps the existing standards, gaps and needs within the action areas used in the workshop. The results from the sub-groups efforts will be compiled and the expert groups anticipate having its first recommendations ready following the summer 2006 (see Section 2). The expert group is a unique constellation where interests from industry, national authorities, as well as the European Commission services, can exchange views and work together for future standardisation. Additional experts are still welcome to join the group.

5. Contribution towards an energy risk-informed society in Europe

As discussed in this paper, past EC JRC activities have tried to map the status of use of risk assessment for different applications, showing that differences in the current approaches to risk assessment across different industries and countries mainly come from the extent to which the sequence of the risk assessment process is taken into account and from the explicit or implicit use of the basic criteria probability of occurrence and extent of damage in some of the process steps (expressed in quantitative, semi-quantitative or qualitative terms).

Standardisation at a generic level is desirable and should focus on the process underlying risk assessment. It should, however, not attempt to harmonise risk acceptance criteria, i.e. not to attempt to lay down what "tolerable" levels of risk might be; that is for governmental authorities on the national level. The main objective of any such effort should rather be to help all stakeholders, incl. the general public, to see more clearly the range of possibilities and to assist decision makers in decisions, which only they can make.

For this reason, what is desirable and realistic with regard to wide acceptance and use is a "template", which maps out the steps in risk assessment in a generic way. The development of such a template should be accompanied by the development and continuous operation of an open reference system, e.g. a web-based Information System, capable to support specific implementation and use of the template. For applications to the energy sector, this is ERMON, supported by a network of experts, SEIF-CV, from different stakeholders to provide and screen relevant information on energy risks.

In the EUs quest towards a liberalized energy market, it is essential that people be aware of risks, benefits and uncertainties related to the different energy sources available in the changing and inter-connected energy landscape. To address the many economic, political, social, technological and cultural pressures on security of energy supply in the EU, it is essential that tools, such as ERMON, and facilitating mechanisms, such as SEIF-CV, be developed on a pan-European level to assist society in making informed choices. ERMON and SEIF-CV also contribute to providing support towards a more consistent EU energy risk management process.

Acknowledgements

Both ERMON and SEIF-CV have already received substantial input from colleagues from various EC services, such as DG TREN, DG RTD and DG JRC, as well as from CEN. The following persons shall gratefully be acknowledged (in alphabetical order): José Antonio Hoyos Pérez (TREN), Augustin Janssens (TREN), Stanley Morris (JRC), Ioannis Samouilidis (TREN), Manuel Sánchez Jiménez (RTD), Helena Sellerholm (Swedish Standards Institute, Member of CEN), Marc Steen (JRC).

References

Colli, A., Kirchsteiger, C., 2005. Development of a General Life Cycle Scheme for all Energy Technologies, European Commission, DG JRC, Institute for Energy, Petten, EUR21735EN.

Hohenemser, C., Kates, R.W., Slovic, P., 2000. The Nature of Technological Hazards. In: Slovic, P. (Ed.), The Perception of Risk – Risk, Society and Policy (Chapter 10). Earthscan.

Kirchsteiger, C. (Ed.), 2002. International workshop on promotion of technical harmonization on risk-based decision-making. Special Issue of Safety Science 40 (1–4).

Sellerholm, H., 2006. Minutes of the 8th meeting of CEN/CENELEC Joint expert group Critical Infrastructure – Energy Supply held on 8.6.2006 in Stockholm, CEN/CLC Joint EG Energy Supply, N044.

Vetere Arellano, A.L., Kubanyi, J., Kirchsteiger, C. (Eds.), 2005. In: Proceedings of the JRC/OECD Seminar on Risk & Emergency Zoning around Nuclear Power Plants, European Commission, DG JRC, Institute for Energy, Petten, EUR21734EN.

Available online at www.sciencedirect.com
ScienceDirect
Safety Science 47 (2009) 59–77
SAFETY SCIENCE
www.elsevier.com/locate/ssci

Risk characterisation indicators for risk comparison in the energy sector

A. Colli [a,*], A.L. Vetere Arellano [a], C. Kirchsteiger [a,1], B.J.M. Ale [b]

[a] *EC DG Joint Research Centre, Institute for Energy, P.O. Box 2, 1755 ZG, Petten, Netherlands*
[b] *TU Delft, Faculty of Technology, Policy and Management, Jaffalaan 5, 2628 BX, Delft, Netherlands*

Received 20 April 2007; received in revised form 19 December 2007; accepted 16 January 2008

Abstract

The paper presents and discusses steps in the development of a set of risk characterisation indicators (RCIs) to be applied for the comparison of risk expressions from different energy systems across their fuel/life cycle to obtain a fair risk evaluation. The Joint Research Centre of the European Commission (EC-DG JRC), and specifically its Institute for Energy in Petten/Netherlands (JRC-IE), initiated a PhD study activity entitled European Energy Risks Monitor (ERMON), to assess and compare different energy technologies. The comparison is based, among others, on a set of risk indicators, developed on the backbone of a causal structure for energy technologies. The development of the RCIs is a process which aims at the identification of the input for the development, starting with the recognition of possible stakeholders for ERMON, the detection of possible risk scenarios available from different energy systems, and concluding with the development of the indicators. This paper mainly focuses on the latter. The main characteristics of the resulting set of indicators are presented and discussed, together with their application, and limits.

1. Introduction

This paper focuses on the development of a set of Risk Characterisation Indicators (RCIs), to facilitate the comparison of energy risks from comparing risk expressions from different energy systems. In this paper, an energy system is a complex process that transforms a primary energy source (substance or natural phenomenon) into useful power (that can be thermal, electrical, mechanical), taking stock of various multi-dimensional aspects (human factors, technology, organization, policy, interactions with the environment, etc.). It is important to highlight the human factors aspect, because people are involved in the energy system both as executors of the fuel transformation and conversion, but also as end-users. Different definitions of risk are available from the literature. In this paper risk is expressed as the combination of consequences and probabilities. Taking this definition into account, energy risks involve accidental or voluntary events, with different probabilities, coming from normal operation or non-planned internal and/or external (to the involved technology) events resulting in human, economical, and environmental consequences. Energy risks are reported as risk expressions.

Risk expressions cover a large variety of forms. They can be numerical (probabilistic safety assessment results, economic damage data, etc.) or can be represented by a verbal statement (reports, news releases, etc.), based on historical data or on prognostic studies. This fact leads to difficulties in making comparisons for non-experts, along with the related challenges of communicating results.

Moreover, the qualification environment of these risk expressions can be very different, leading to a very different quality level of the information provided.

The data underlying these estimates can originate from technology specific probabilistic studies, from specific historical operating experience or from transfer of operating experience from similar (generic) technology to the specific

* Corresponding author. Tel.: +31 224 565027; fax: +31 224 565623.
E-mail addresses: alessandra.colli@jrc.nl (A. Colli), ana.vetere@jrc.nl (A.L. Vetere Arellano), christian.kirchsteiger@ec.europa.eu (C. Kirchsteiger), b.j.m.ale@tbm.tudelft.nl (B.J.M. Ale).
[1] Present address: Directorate-General for Energy and Transport, Rue Robert Stumper 10, L-2557 Luxembourg.

0925-7535/$ - see front matter © 2008 Elsevier Ltd. All rights reserved.
doi:10.1016/j.ssci.2008.01.005

one of interest. Furthermore, risk expressions can be based on different types of models, quality assurance and peer review schemes, etc.

The planned Energy Risks Monitor (ERMON) Information System is expected to allow end users to carry out a fair comparison of the final results of any existing risk expressions (from risk assessment studies and incident/accident statistics) for different energy systems across all steps in their specific fuel cycle chains.

ERMON adopts a methodology based on indicators to score the degree of risk and to qualify the background of the information.

Thus the comparison focuses on two different aspects:

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

The first aspect leads to the development of a set of Risk Characterisation Indicators (RCIs), while the second aspects lead to a set of Risk Qualification Indicators (RQIs). 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.

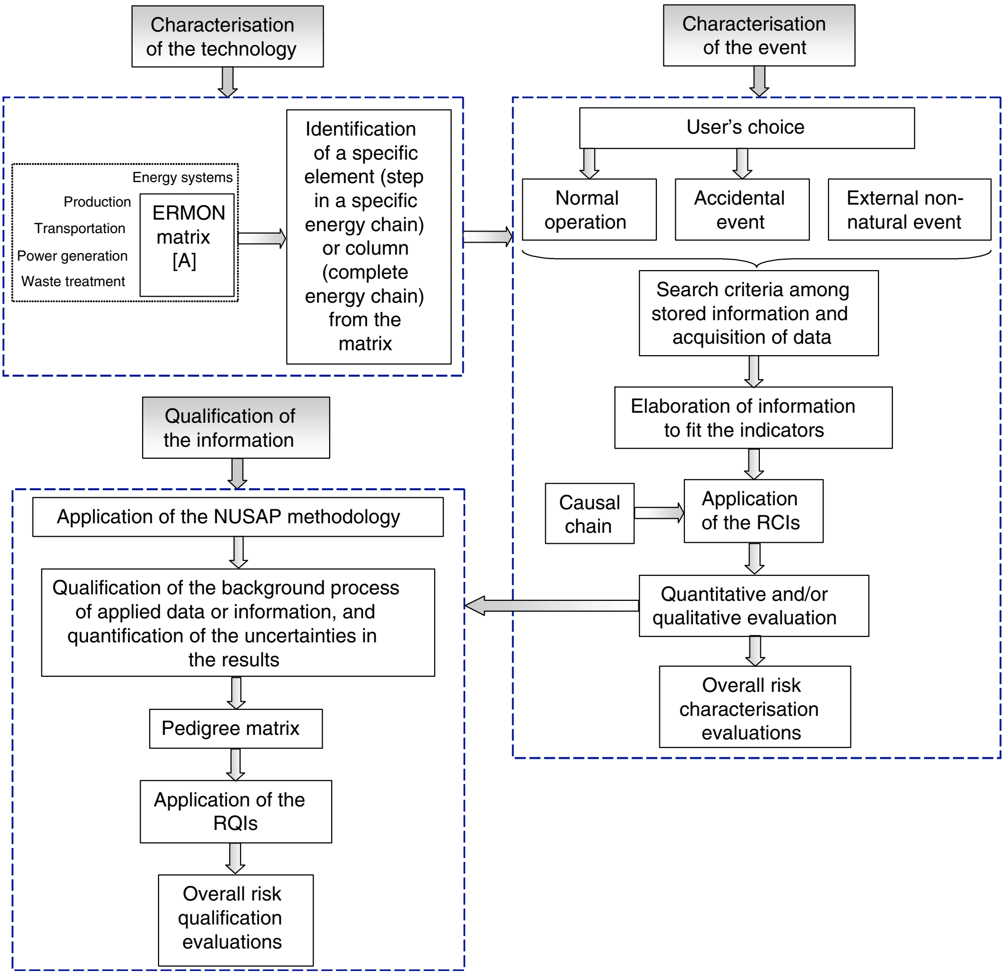


Fig. 1. ERMON methodology scheme, highlighting the three processes of characterisation of the technology, characterisation of the event, and qualification of the information.

Fig. 1 shows in a schematic form the methodology of ERMON through the most relevant steps, using a three-block structure.

1. *Characterisation of the technology*: the first approach to the development requests to determine a group of energy systems to consider, which are identified in fossil fuels (coal, oil, and natural gas), nuclear energy, renewable energies (biomass, geothermal, hydro power, solar energy, and wind energy), and hydrogen. The subsequent analysis of these technologies along their fuel/life cycles leads to the identification of a general chain scheme adaptable to all of them (Colli et al., 2005a). This scheme is characterised by four main steps:
   (a) Production – related to all production operations.
   (b) Transportation – all transportation steps, including raw material, waste, and storage.
   (c) Power generation – power plant, including construction and dismantling operations.
   (d) Waste treatment – waste from the power plant as well as from other production activities. Waste can be treated or can be sent to a final disposal.

   The development of such a general scheme, together with the identified energy systems under consideration, lead to the identification of a matrix [A], which is built up with elements a_{ij}, where i = step in the general fuel/life cycle, and j = energy technology. The matrix represents the basis for the development of the ERMON tool. The filling level in the matrix is associated with the correspondent complexity of the chain analysed. The matrix [A] could allow reaching different levels of information, identifying a single step in a specific chain or a complete chain. The chosen element (single matrix element or entire column) is then expressed in indicator form.
2. *Characterisation of the event*: to describe the risk level of the event into consideration, a set of Risk Characterisation Indicators (RCIs) is developed. Events can be chosen among the categories of normal operation, accidental events, and external non-natural events. This part is discussed more in detail later in the article.
3. *Qualification of the information*: the qualification aspects of the event will be carried out based on the NUSAP (Numeral Unit Spread Assessment Pedigree) methodology. As reported by S.O. Funtowicz and J.R. Ravetz in the book "Uncertainty and Quality in Science for Policy", NUSAP addresses different types of uncertainty in a risk assessment, along with the quality of the information supporting the assessment. NUSAP allows to address uncertainty and quality at different locations in a risk assessment, including input data, parameters, scenarios, model structure, model assumptions, indicators used, model system boundary, and problem definitions. NUSAP provides a systematic critical review of the available knowledge base for each of these risk assessment components and pinpoints specific weaknesses in the underlying knowledge base. It helps in assessing robustness of outcomes of a risk assessment in view of the uncertainties identified and in the setting of priorities for the improvement of the quality. This methodology will be applied to qualify the results of the RCIs.

The scope of this work is limited to aspects related to the development of a set of Risk Characterisation Indicators (RCIs) to compare risk expressions.

In accordance with the definition Stern and Fineberg (1996) proposed for risk characterisation: "*risk characterisation is a synthesis and summary of information about a potentially hazardous situation that addresses the needs and interests of decision makers and of interested and affected parties. Risk characterisation is a prelude to decision making and depends on an iterative analytic-deliberative process*", RCIs aim to provide information on the specific risk under consideration and must respond to the need of the different kinds of users involved in decision making processes. This statement led to a preliminary investigation of possible ERMON users, their needs, and also the types of energy risks to consider in the development of the RCIs. This in turn led to a set of *event-specific* characterisation indicators, which will be then normalised and will become *energy-specific* in a final overall consideration of ERMON.

In summary, Sections 2–4 describe the background information used to develop the RCIs, whilst Section 5 portrays the RCIs in detail. Section 6 is dedicated to the RCI applications and limits and Section 7 provides one case study where the RCIs are implemented, which is then followed by some conclusions (Section 8).

2. Methodology

The relevance of using indicators as a way to address risk comparison is discussed by Gray and Wiedemann (1999).

> *"Indicators are a basic tool of management in any sphere, in particular for describing and monitoring the situation being managed, to help assess the available management options, and to evaluate the outcomes of actions taken. In addition, indicators are important in the communication between various stakeholders, which is involved in all these functions. The basic, inherent difficulty with indicators is that they are selective. They each represent one measure of one aspect of any situation. This means that there is always room for discussion and even disagreement about whether they really represent that which one wants to measure; whether other people want to measure the same thing; and whether the measure is understandable to non-experts (*Gray and Wiedemann, 1999*)."*

The reported statement also highlights a basic difficulty when dealing with indicators: the problem of the clarity and exactness of definitions. Indicators should be clearly defined, especially in such a wide area as represented by energy systems. In this context, definitions play a fundamental role.

The aim of ERMON is to develop indicators that facilitate and provide a framework for energy risk comparison.

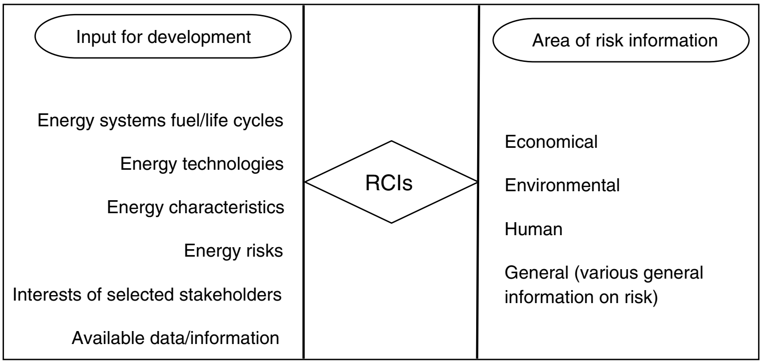


Fig. 2. Input used for the development of the RCIs, and areas of risk information covered by the indicators.

The selected RCIs would be applicable to all energy systems in a way to make comparison easier, expressed by common units or designations, and thus comprehensible not only to experts. To obtain the set of indicators, various main inputs are initially taken into consideration (see Fig. 2). Fundamental is the appropriate knowledge of the energy systems to be considered, along with the investigation of their fuel/life cycles. Energy technologies, characteristics, and expected risk scenarios are also analysed. There are many possible risk scenarios for energy systems, with different impacts and importances, including multi-dimensional risks (human, environmental, economical, etc.). Moreover, energy technologies cover a wide range of systems, different according to adopted primary energy source, equipment, machinery, processes, etc. This prior investigation leads to the identification of what the indicators should represent, with respect to importance and risk significance. In addition, the possible available data and information to be used should be also taken into account, which dictates the investigation level of the indicators. Finally, but not less important, is the identification of the possible stakeholders, and their needs.

The scope of the ERMON tool is to communicate energy risk results through normalised values in a clear form to a large variety of stakeholders, to allow reasonable energy risk understanding and comparison.

The choice of using indicators has been done taking into account the large public, which ERMON would like also to address. A basic zero to one scale with common units was used to enable comparison and communication with the indicators.

The groups of identified ERMON users are mainly (see Fig. 3): governmental bodies at all levels, including government-related activities; NGOs, including commercial and non-commercial interest groups; institutions for public and private research; commercial stakeholders; acting-alone individuals; and the media, which act as a conduit of information, but also can affect the opinions of the other stakeholders. The above-mentioned stakeholders have a large variety of interests, and ERMON should be able to address them all.

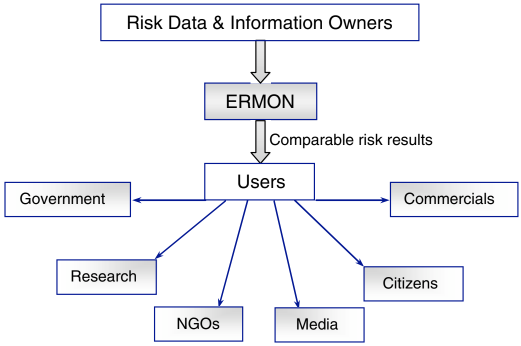


Fig. 3. ERMON links with upstream data and information owners, and downstream possible stakeholders.

To unify the approach to such a broad area, it is necessary to use a model, which can easily be adapted to different processes, and can integrate their characteristics in a format easily understood by all interested parties.

The choice has taken into consideration the causal model, which has the capability to generalise the sequence of events of energy technology hazards in a form adaptable to all energy systems, using indicators to characterize the significant steps of the causal structure.

The development of the indicators is done following the example of the causal structure for hazard development in energy systems of Hohenemser et al. (2000).

Fig. 4 shows the application logic of the RCIs, which, as previously indicated, are event-specific. Various events, with inhomogeneous background information, can be filtered by the ERMON's RCIs to reach comparable results on the same level of information at the final stage.

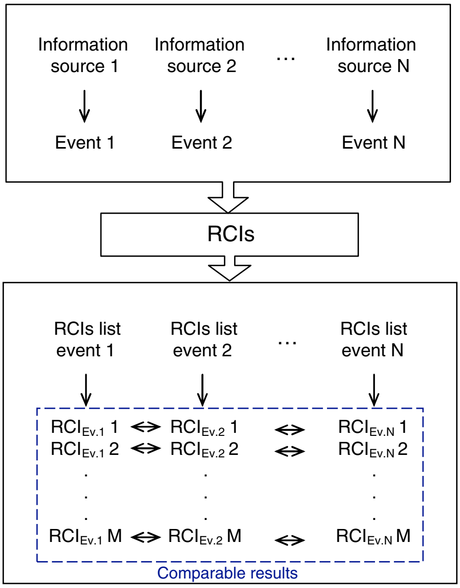


Fig. 4. Application procedure of the RCIs. They will be applied to single events with inhomogeneous information, to reach comparable results.

3. Risk scenarios in the energy sector

The process that leads to the development of the RCIs has its basis on the investigation of the possible risk scenarios in the energy sector.

The investigation is carried out in two directions; one takes into consideration the type of events and tries to classify them, while the second investigates the causes and the impacts on the designated areas. According to the scheme shown in Fig. 5, external risk concerning energy systems can be classified into three different categories:

1. Risks from normal operation.
2. Risks from accidental events (routine, severe, including risks from natural disasters).
3. Risks from external non-natural events.

The larger development of the risk side is not associated with the dominance of risks in the energy sector, but it is only related to a deeper investigation to fulfil the scope of this study. Electricity production offers a wide range of benefits, from the energy availability for different purposes, leading to industrial, and thus economic, development of the society, improving welfare, and societal independence from other countries, boosted by independence from external energy sources when possible. Anyhow electricity production has also a series of associated risks, mainly divided into direct economic and external, the first related to the energy market, and the second involving events external to the electricity itself as product.

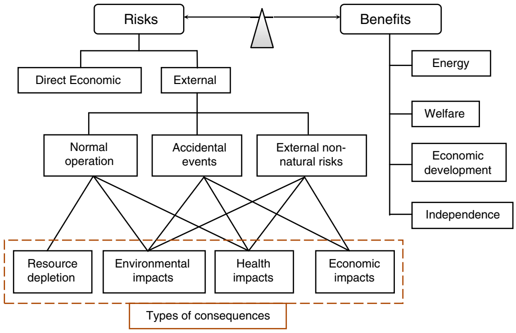


Fig. 5. Framework for evaluation of fuel/life cycle risks in electricity production (Fthenakis et al., 2006).

The first risk category is triggered by elements at one or more stages of the fuel cycle for each technology; these events are common in normal operation and are not considered accidental. Their impact is usually limited by the enforcement of safety procedures during normal production (Fthenakis et al., 2006).

Ordinary toxic chemical emissions, as well as radioactivity releases due to normal operation activities can be listed under this category. Issues like greenhouse gases (GHG) emissions and resource depletion are clearly sustainability-related. The authors are conscious of the importance of sustainability concepts, and ERMON as tool will not be considered completed without adding the related issues. It is accepted that the two concepts of risk and sustainability are both very important for managing energy related decisions (see also Gray and Wiedemann, 1999). The plan is, in fact, to integrate ERMON with added indicators to cover sustainability aspects; however, this is not the scope of this PhD study. At the moment, only external sustainability studies are referenced, e.g. indicators for GHG missions and available resources and reserves for critical fuels can be found in (IAEA et al., 2005).

A larger variety of events are then listed among accidental events, which are further characterised by the step in the chain and the energy technology under consideration, or events can also be triggered by natural disasters.

This second category analyzes 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, which are also less easily reported especially when the consequences are minimal.

This reflects the importance of taking into consideration "extreme" events as highlighted in (Haimes, 2004): *"For risk methodologies and tools to be useful and effective, they must be representative; that is, they must capture not only the aver-*

age risks, but also the extreme and catastrophic ones." Average values are not enough to judge and prevent low-probability catastrophic situations. To be prepared to face expected unacceptable risks, modern decision analysts need to focus on also on expected maximum risk. Calamities, such as dams bursting and nuclear-reactor meltdown, are good examples. Extreme events are considered in ERMON to set upper limits for the risk indicators. The maximum value, associated with the maximum outcome for the specific indicator into consideration, has been set considering catastrophic events and examining available historical records. The importance of the maximum value is also recalled by highlighting the maximum result among the indicators applicable to a specific event, or series of events.

The third category encompasses events that may be triggered during a specific fuel-cycle stage but whose consequences are not amenable to 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 (Fthenakis et al., 2006).

This category aims to consider issues related to geo-political instability, military conflicts or nuclear proliferation, which could be easily converted into the general problem of intentional terrorist actions and attacks to energy infrastructures with the intent to harm the population and cut the energy support in one or more countries. The case of terrorist attack against energy infrastructures is distinguished from events of the second category for the difference in the originating cause, not due to an intrinsic property of the system, but to the intentionality of the event.

The nuclear chain has to consider also the added risk related to nuclear proliferation, where nuclear knowledge, technologies, and materials can be used for the construction of nuclear weapons for war or terrorism purposes.

With a global view of the different types of energy-technology-related risks, it is possible to describe events in terms of release of material (through atmospheric, liquid and solid pathways) and/or energy.

When treating the context of energy security, national energy independence is also relevant, but clearly sustainability related; as explained earlier, sustainability concepts will be taken into consideration in the near future. This topic has also already been considered in other studies – see, for example, the net energy import dependency indicator ECO 15 from (IAEA et al., 2005), or the case of supply/demand and crisis capability indicators from Scheepers (2006).

To give a valid support to the choice of the indicators, an investigation of the possible risk scenarios for different energy systems are evaluated and analyzed.

Within ERMON, as shown also in Fig. 5, the consequences will be evaluated for three aspects of interest for risk:

1. Human.
2. Environmental.
3. Economical.

Moreover attention will be paid to time frame, and occupational and non-occupational aspects. Considering the health impact, effects of energy systems on *humans* can come from the following paths:

- Inhalation (e.g. toxic fumes, gases, etc.).
- Direct contact (e.g. materials, harmful substances, etc.).
- Thermal energy (e.g. fire).
- Mechanical energy (e.g. explosions, crashes).
- Radioactivity (e.g. radiological effects).

These different causes of risk for people could have different degrees of consequences, which could result in immediate or delayed fatalities, injuries, evacuees, or long-term health effects affecting also future generations (mainly related to radioactivity contamination).

The effects of energy systems on the *environment* (estimated mainly using Externe (1997) and Barbir et al. (1990)) can derive mainly from the release of dangerous substances (with and without radiological effects) and thermal energy, producing consequences on:

- Live stock, with fatalities, injured, permanent damages, effects on future generations and on the animal natural habitat (animal are affected in a manner similar to human beings).
- Contamination of air, ground, water, and environmental goods with high concentration releases.
- Radiological impact level on animals and environment.

Resource and water depletion, global warming, and disturbance to the visual and acoustic amenity of neighbourhoods should also be mentioned as environmental effects, but are more close to sustainability issues and not considered at the moment in the study; they will be introduced later in the project, to complement the risk part.

The *economical* effects of possible risks from energy systems can be separated into two categories: direct (internal economic consequences) and indirect (external economic consequences). The first one includes property and rebuilding costs or remedy for prevention/substitution. The second category is then separated into environmental (impact on public and occupational health, agriculture, forests, biodiversity effects, aquatic impact, impact on materials, global impact) and non-environmental (impact on public infrastructure, security of supply, government actions) effects (Hirschberg, 1998).

4. Causal chains

The approach of causal taxonomy using a causal model has been developed by a group of researchers (C. Hohenemser, R.E. Kasperson, R.W. Kates) at CENTED (Center for Technology, Environment and Development) at Clark University in the eighties (Hohenemser et al., 1985). The Clark University causal model conceptualizes hazardous events as part of a causal sequence, beginning with a human need or want and evolving into a series of occurrences and consequences that cause harm to humans or what they value. The original causal sequence consists of seven stages (human needs, human wants, choice of technology, initiating events, outcomes, exposure, and consequences) with one leading to the other through causal pathways (Hohenemser et al., 1985). The initial aim of this model was to help in the comparison of different technological hazards, but it was later adapted to a large number of applications, including also the comparison of environmental hazards (Kasperson and Kasperson, 2001). A causal sequence approach has also been used for the prevention study and the mitigation activities concerning accidental releases of hazardous gases in photovoltaic manufacturing facilities, highlighting also the point of intervention to mitigate hazards along the chain (Fthenakis, 2001).

Once the causal chain is fixed as a backbone to understand the causal development of energy hazards, it is then necessary to identify a method to highlight the characteristics of every step in a measurable way. The methodology is offered by C. Hohenemser, R.W. Kates and P. Slovic in their work "The nature of technological hazard" (Hohenemser et al., 2000). Here they study technological hazards as a sequence of causally connected events, involving potentially harmful releases of energy and materials, based on a causal sequence, 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. To differentiate among different types of hazards, the work defines and presents 12 measures for individual hazards to be applied at the appropriate step in the causal chain. The 12 indicators have relevant characteristics that are applicable to all types of technological hazards, comprehensible to nonexperts and expressed in common units.

The indicators presented in (Hohenemser et al., 2000) are numerically quantified partly by a categorical distinction (intentionality, transgenerational, potential non-human mortality and experienced non-human mortality) and partly by a logarithmic scale (spatial extent, concentration, persistence, recurrence, population at risk, delay of consequences, annual mortality and maximum potentially killed). The choice of a logarithmic scale allows a practical representation, with the quality of matching human perception better than linear scales (like the decibel sound intensity scale or Richter earthquake intensity scale).

The purpose of this section has been only to briefly introduce the methodology adopted in the development of the set of RCIs for the ERMON project. For any deeper analysis of the model here presented, and the related indicators and scoring system, it is suggested to refer to Hohenemser et al. (2000).

When looking into different energy systems the basic problems are the variety of technologies encountered, the different possible hazardous situations, together with a large number of dissimilar risk expressions. This situation prompts the need to look for a general model, which could be easily adapted to different situations, and, at the same time, permits to assess the diverse available risk information. The authors have chosen Hohenemser et al.'s model due to its high degree of versatility, which allows it to be applied to different cases and situations, in a unique identical configuration.

Fig. 6 shows the causal structure model adapted to the case of hazardous release of energy and/or material from energy systems.

Using the causal sequence model helps identifying common characteristics of energy hazards in order to simplify their analysis and management across a limited number of steps. Implementing the causal model with the adoption of indicators, allows expressing energy risks in common units, with the aim to assist non-experts better understand and compare different risks.

These are all important attributes that must be present in ERMON, as it wants to refer to a large variety of energy systems, as well as stakeholders.

5. ERMON's risk characterisation indicators

The process to develop the set of RCIs to be used in ERMON is based on the backbone of the causal structure, according to the sample offered by Hohenemser et al. (2000).

For the purposes of ERMON, and taking into consideration the previously conducted investigation among the possible risks in the energy sector, the causal structure has been slightly modified, resulting in the sequence shown in Fig. 6.

The model of hazard causation anchors at one end human needs, and at the other consequences, linked through a causal sequence of steps. Human needs and human wants generate energy-related activities, which produce changes in material fluxes, that are the origin of changes in valued environmental background components, for routine or accidental events; these changes induce some exposure that have some consequences to people and things that they value.

In the context under investigation, human needs refer to the possibility of using energy, available in the form of electricity or heat, for personal well-being, societal growth or industrial activities.

The choice of the technology is then related to the identification of the specific energy system under analysis, evaluated along its fuel/life cycle, which constitutes the primary source of the evaluated risk.

According to the chosen system, specific events are considered, which can generate a release of material or energy according to different modalities, forms and pathways. This release is going to change the usual natural back-

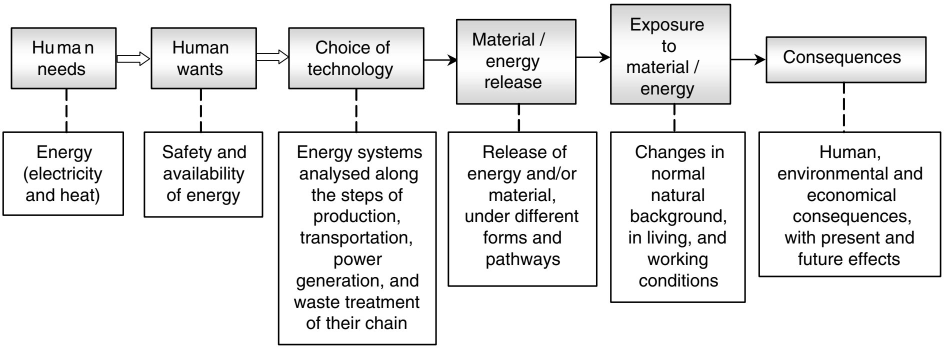


Fig. 6. The causal structure of energy systems, considering as hazard a release of energy and/or material.

ground, against which the level of exposure is defined, leading then to specific human, environmental and economical consequences.

Each link in this chain may be described by some characteristics, and each characteristic may then be described by a measurable indicator (normalised numerical scale). Specific indicators are identified at different stages in the causal structure.

The sample risk indicators of Hohenemser et al. (2000) were implemented and modified to be adapted to the energy technology environment within ERMON. Several in-depth studies to analyse specific risks and events in selected industrial sectors were carried out: natural gas transmission pipelines (Colli and Kirchsteiger, 2004), chemicals threats from the photovoltaic manufacture industry (Colli et al., in preparation), along with a first attempt to apply a preliminary group of modified indicators to open source information concerning two well-known nuclear accidents (Colli et al., 2005b).

The aim of this first trial application was the need to further develop the indicators and extend them to incorporate other aspects (like the economical ones). Fig. 7 portrays the list of RCIs, which are also enhanced by other additional indicators listed in the last part of Table 1.

A complete set of 21 elements has been obtained (Colli et al., 2007), which can be classified into the following groups:

1. The *RCIs*, which group seventeen indicators related to the causal chain in Fig. 7. Among these indicators, there are those known as the *core* RCIs, which are those resulting in a numerical value, that will finally allow a

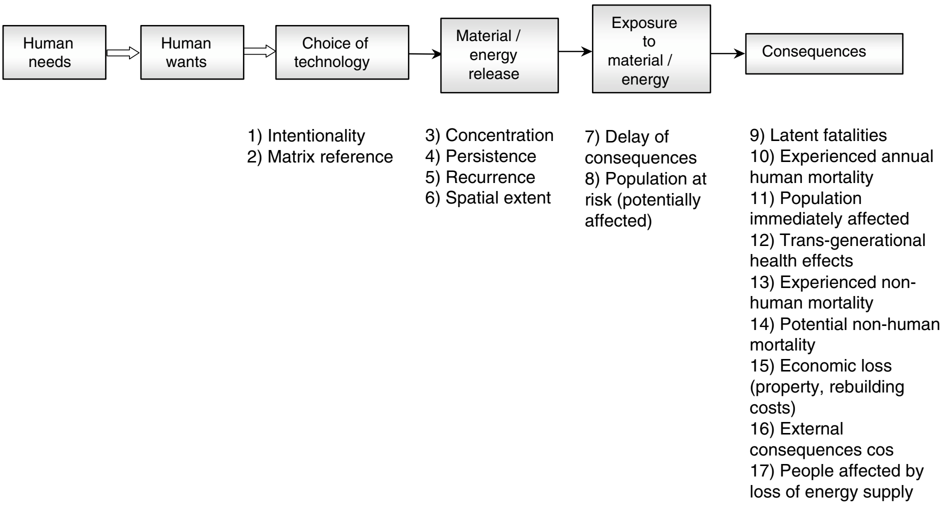


Fig. 7. Causal structure for energy systems and set of RCIs developed for ERMON. The causal structure outlines the steps leading to hazard development, from the origin to the consequences. Every sequence level is described by the connected indicators listed below. The information related to incidents/accidents is the input for this structure, while the output is offered by the assessment of the indicators application.

Table 1
Summary table of all indicators and their main characteristics

Identification code	Indicator	Sub-classification	Definition	Area of risk (only for core RCIs)	Specificity (only for core RCIs)
CT-01	Intentionality	Accidental event External non-natural event Normal operation	Definition of the level of intentionality of the event into analysis, distinguishing into accidental event, external non-natural event, and normal operation	–	–
CT-02	Matrix reference	Element Column	Identification of a fuel or life cycle in one of its main steps, or in total. It defines the element a_{ij} (energy system and step of chain) or the column (all chain) of the ERMON matrix $[A]$. $i =$ production, transportation, power generation, waste treatment, all. $j =$ one of the identified energy systems	–	–
MER-01	Concentration	Material Energy Nuclear radiation	Concentration of released energy or materials, relative to a threshold considered significant	General	General
MER-02	Persistence		Time over which a release remains a significant threat to humans	General	General
MER-03	Recurrence		Mean time interval between releases above a minimum significant level	General	General
MER-04	Spatial extent	Internal External (numerical division)	Maximum distance over which a single event has significant impact	Environmental	General
MEE-01	Delay of consequences		Delay time between exposure to hazard release and occurrence of consequences	General	General
MEE-02	Population at risk (potentially affected)	Occupational Non-occupational Global value	Maximum number of people potentially affected by the hazard (e.g. under less favorable conditions)	Human	General
C-01	Latent fatalities	Occupational Non-occupational Global value	Number of people affected by latent effects. The latent fatalities are represented by the sum of late and delayed fatalities	Human	Specific
C-02	Experienced annual human mortality	Occupational Non-occupational Global value	Average annual deaths	Human	General
C-03	Population immediately affected	Occupational Non-occupational Global value (all with further division into: fatalities, injured, evacuees, global value)	Number of immediate fatalities and/or injuries and/or evacuees in a single event	Human	General
C-04	Trans-generational health effects	Human Non-human	Number of human/non-human future generations at risk of adverse health effects	Human, environmental	Specific
C-05	Experienced non-human mortality		Dead animals that have occurred	Environmental	Limited
C-06	Potential non-human mortality		Maximum potential dead animals	Environmental	Limited
C-07	Economical loss (property, rebuilding costs)		Property and rebuilding costs of the damaged facility	Economical	General
C-08	External consequences cost	Environmental Non-environmental	External costs related to the event into analysis at different levels. Environmental: Impact on public and occupational health, agriculture, forests, biodiversity effects, aquatic impact, impact on materials, global impact. Non-environmental: Impact on public infrastructure, security of supply, government actions	Economical	General
C-09	People affected by loss of energy supply		Number of people affected by loss/reduction of foreseen energy supply	Human	General
IB-01	Source identification		Identification of information provider	–	–

(*continued on next page*)

Table 1 (*continued*)

Identification code	Indicator	Sub-classification	Definition	Area of risk (only for core RCIs)	Specificity (only for core RCIs)
IB-02	Type of risk information	Historical Probabilistic study	Distinction between risk information from actual events (historical) and from probabilistic studies (risk expressions)	–	–
RS-01	Risk significance	AHP value Maximum value	Overall values calculated from the RCIs single values	–	–
VI-01	Completeness		Level of completeness of the RCIs respect to the total of them	–	–

mathematical processing evaluation to rank risks. The core RCIs are those numbered from 3 to 17 in the list of Fig. 7.

2. The *additional indicators*, which collect additional information to complement the RCI-related information. These are: source identification, type of risk information, risk significance, and completeness (codes IB-01, IB-02, RS-01 and VI-01 in Table 1.

Each of these indicators presents an evaluation method. The core RCIs can be evaluated on the basis of numerical and/or verbal statements extracted from the source of information. Both numerical-based and verbal-based evaluations are ranked according to correspondingly different scales, and finally converted into a normalised 0-to-1 scale.

The same normalised scale is also applied to the additional indicator VI-01 (completeness), which is the ratio between the number of indicators that received information and their total. This ratio provides knowledge about the richness of the scores available through the RCIs.

The remaining indicators are evaluated on a verbal basis, through a free text or a pre-determined text. Finally, the additional indicator RS-01 (risk significance) is the result of mathematical processes, which allows selection of the methodology applied, followed by a numerical result. Risk significance is a relevant indicator, which communicates a judgment about the subjective importance of different risk events and highlights relevant values among the piece(s) of information under analysis. With this indicator, two methodologies are used:

1. The Analytical Hierarchy Process (AHP) – to rank different risk events.
2. The maximum value – to highlight the maximum relevant value(s).

The Analytical Hierarchy Process (AHP) is a decision making mathematical process developed by Saaty (1980). It involves building a hierarchy (ranking) of decision elements and then making comparisons between each possible pair in each group (as a matrix). This gives a weighting for each element within a level of the hierarchy, and also allows the calculation of a consistency ratio (useful for checking the consistency of the data). The AHP provides an effective means to deal with complex decision making and allows a better, easier and more efficient identification of selection criteria, their weighting and analysis. The AHP's strength is its ability to capture both subjective and objective evaluation measures, providing a useful process for checking the consistency of the evaluation.

In addition to the AHP and the ranking process, it is considered that maximum consequences are of great interest in risk evaluation, as also stated in (Haimes, 2004). Considering maximum value(s) avoid the misinterpretation of events, and help stakeholders to highlight important outcomes of a certain risk scenario.

When applying this concept to the core RCIs, the purpose is to highlight a predominantly high score and to warn the user about this value. The identification of the maximum value can be done across the indicators of a specific application, as well as to identify the highest score of a specific indicator through a certain number of cases.

To have a clear knowledge of the considered situation, the maximum value should be always accompanied by the values of all the indicators linked to the event under analysis.

These RCIs have been developed based on consequences and probabilities but not on causes. For the authors, the causes have already been previously considered in specific incident/accident reports, risk assessments, etc., whose results are then fed into the ERMON model.

Moreover, the development has taken into consideration the possible information available for their prospective applicability, covering the main human, environmental and economical aspects of risk.

The core RCIs have been divided into three categories: general, limited and specific, in relation to their applicability to the different chosen energy chains (coal, oil, natural gas, nuclear, biomass, geothermal, hydro, solar, wind and hydrogen as an energy carrier). The majority of the core RCIs has "general" applicability (specificity column in Table 1), which means that they are applicable to all the energy chains taken into account in the investigation. Two indicators (experienced non-human mortality, and potential non-human mortality) are expected to be applicable to five energy chains (coal, oil, nuclear, hydro and wind), while other two (latent fatalities and trans-generational health effects) are "specific" and their application is mainly restricted to the coal and nuclear chains.

Indicators identified as 'general' can be applied to a large number of energy technologies, while those with 'limited' or 'specific' applicability describe mainly the characteristics of specific energy chains, always taking into account the technology and the fuel, or the carrier involved in the process.

The two specific indicators listed in Table 1 have been developed with specific attention to radiological effects arising due to radioactive releases possible in the nuclear chain and, in minor but not negligible part, in the coal chain (Gabbard, 1993; World Nuclear Association, 2004).

The analysis across the specificity of the core RCIs finds a partial correspondence also in the results of the possible available data and information resources for application. The probability to find data for the core RCIs is evaluated using a high/medium/difficult scale, but when an indicator has no application in a given energy chain, then the probability to find information is classified as "improbable".

Resources are very different and the information has to be collected taking into account this diversity. When identifying each probability to access resources for every single indicator, it is necessary to consider not only incident/accident databases, but also other available reported risk-related information (accident reports, lessons learned reports, etc.), and risk assessments. In some cases the data to be used to fill in the indicators can be directly available in the correct form and measurement system, but in other cases they must be elaborated from the original source.

Conventional energy sources present the higher availability of data and information. This is due to the long time use of these technologies during the past decades, mainly in the form of centralized energy production. Incidents and accidents have been collected since long time, especially by the industry itself. However, at times, access to this information can be difficult due to confidentiality issues (during the accident investigation, company policy, etc.). There is also historical data available, as well as risk studies, which are accessible online or upon request to the company.

Renewable energy technologies, with the exception of hydropower, have experienced an extraordinary growth especially in the last years, while in the past their use was very limited.

Renewable technologies in some cases are quite new, still in development to be competitive in the energy market, and their applications are mainly in the form of distributed generation, with limited power rates of the installations. Renewable energies are often considered as complementary to conventional energy sources. Their use is still quite limited compared with fossil fuels or nuclear, thus there is less available information on renewable energy-related events and a limited number of significant risk events, leading to difficulty in finding information to be applied in ERMON, as is the case, for example, in the solar and wind energy sectors.

Besides the situation of renewables, hydrogen presents the same problem, being a new technology approaching the energy market. Hydrogen had a very limited use in its historical background as an energy carrier, and results in risk information being very difficult to find and collect.

Hydrogen, as an energy carrier, could be criticized when listed together with energy fuels. The authors have taken the decision to list hydrogen among the other energy chains, with the knowledge that the level of hazard relies also on the consideration of its production pathway. This decision has been taken considering ERMON's scope. ERMON indicators have been developed with the idea in mind that this information tool should not consider the risk of the energy source in itself, but has to evaluate the technologies adopted in processing a certain fuel, according to its fuel or life cycle.

From this point of view, hydrogen technologies are not an exception and should be included as well, as relevant energy technologies for the future of electricity production.

The discussion carried out in this section is not intended to be an absolute evaluation of the core RCIs, but is a humble proposal of the authors, elaborated with the support of the expertise of relevant researchers in the energy fuel/life cycle assessment arena.

6. Application and limits

The indicators are applied to single events (incidents/accidents) and single pieces of information related to one or more steps along a specific energy chain (e.g. an explosion during natural gas pipeline transportation for the first, and a report concerning threats of nuclear energy in the latter). Different parallel applications of the risk indicators allow a cross comparison among the chosen events. Comparison among energy chains will be allowed as a final outcome of a large number of information gathered through ERMON and normalised according to the energy production (MWh) per fuel or life cycle on annual basis.

To avoid inconsistencies, the comparison of two or more events should follow specific criteria:

- The events should be related to the same level of the fuel or life cycle under consideration, or, at least, they should take into consideration similar processes.
- The events should be 'technically' similar (e.g. comparison of different explosions concerning natural gas and oil).
- The indicators adopted for the comparison should have obtained an evaluation for all the events analysed. If information on one indicator has been provided for only some events, but not for some others, then this indicator should be excluded from the comparative process.
- If possible, the original format of the information can be used for a given indicator; however, it may be the case that information needs to be elaborated or interpreted before using the information.

It is not necessary to have information for all the indicators for every event analysed, but the higher the number of indicators available for the comparison, the more complete the information and the outcome will be.

Once ERMON will be developed and a large amount of data and information will available from different sources, then the comparison of single events and pieces of information could be completed to provide general trends about risks in different energy sectors and energy technologies, based on annual energy production by technology. This would also allow validation of the comparison of single events among different energy systems, with the overall risk trends among the same considered energy sectors. The application of the risk indicators is a process with a high degree of subjectivity. The involved user is asked to give his/her opinion throughout the entire process of information collection for the application of ERMON indicators. Also in the final judgment, the application of the Analytical Hierarchy Process is a clear example of subjective method of evaluation, which involves the interests and the particular characteristics of the user.

The subjectivity of the process has to be taken into consideration for a clear understanding of the results of the indicators. In the next development of the risk qualification aspects, this issue will be undertaken to highlight the reason behind certain choices and special qualitative indicators (Risk Qualification Indicators – RQIs) will be introduced to classify the quality of results obtained.

From the practical point of view, the application of the RCIs follows the scheme initially proposed in Fig. 1.

ERMON is based on a fundamental matrix binding different energy chains with their steps of the fuel or life cycle (Colli et al., 2005a).

Once identified the step taken into consideration, which appears through the indicator CT-02 (i.e. the matrix reference), the user can choose among the three types of available energy risks (normal operation, accidental event and external non-natural event), as previously presented and discussed in Section 3 of this paper. Also this choice is highlighted through an indicator, named CT-01, i.e. intentionality.

Once the selected event or information is defined, then the RCIs are applied to transform the risk expressions in a normalised form, to allow comparison.

The overall risk characterisation scores are represented by the identification of relevant values, like the maximum and the result of the AHP application.

The application of the methodology will be carried out using the ERMON tool (presently an excel spreadsheet model), which requires a high degree of involvement of the interested user.

The limits of the proposed indicators and the applied methodology can be mainly related to the following aspects:

- Subjectivity in the development and in the application of the methodology.
- The indicators are not fully comprehensive of all energy risk aspects.

Table 2
Case study

ERMON general chain			Comparison/on/cases	
Main step	Sub-step of first level	Sub-step of second level	Natural gas	Oil
Production	Exploration			
	Extraction			
	Treatment			
Transportation	Raw material transportation			
	Transportation	Long distance	Pipeline explosion in Carlsbad, NM, USA, 2000 (NTSB, 2000a)	Pipeline explosion in Lagos, Nigeria, 2006 (CNN, 2006)
		Regional		Pipeline rupture and release in: (1) Bellingham, WA, USA, 1999 (NTSB, 1999); (2) Chalk Point, MD, USA, 2000 (NTSB, 2000b); (3) Fork Shoals, SC, USA, 1996 (NTSB, 1996)
		Local		
	Waste transportation			
	Storage	Material storage		
		Waste storage		
		Construction		
	Fixed installation	Operation		
Power generation		Dismantling		
	Transmission/distribution facilities			
waste treatment	Waste reprocessing			
	Waste disposal			

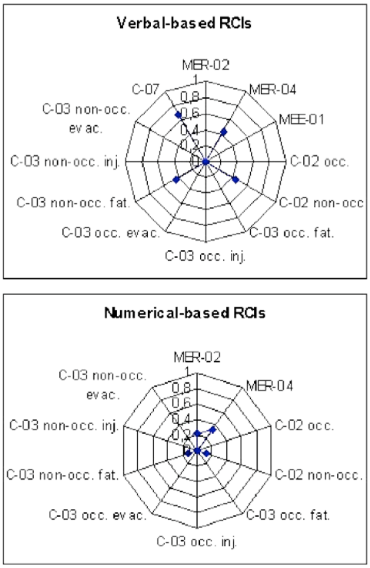
List of the considered cases, linked to the related step in the general chain adopted in ERMON (Colli et al., 2005a).

- Ranking events through the use of the AHP need to limit the number of elements in the comparison (events and/or indicators) to 7 ± 2.
- Absence of sustainability aspects. This is only a temporary limit to be taken into consideration at the present status of the development. Anyhow, the authors plan to complement the RCIs with other sustainability indicators in the near future.

To start with, the first limit is subjectivity, which shows up at different stages of the whole process, from the development to the use. The choice of the indicators is mainly a subjective process. The involvement of the user is one of the main characteristics of ERMON, and the judgement of risk is a subjective process.

Subjectivity is involved in the process itself. The ranking process using AHP is also subjective, and requires the

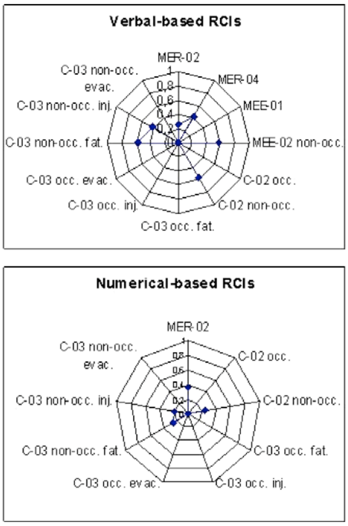
Verbal-based RCIs	
Indicator	Value
MER-02	0
MER-04	0,43
MEE-01	0
C-02 occupational	0
C-02 non-occupational	0,43
C-03 occupational fatalities	0
C-03 occupational injured	0
C-03 occupational evacuees	0
C-03 non-occupational fatalities	0,43
C-03 non-occupational injured	0
C-03 non-occupational evacuees	0
C-07	0,67



Numerical-based RCIs	
Indicator	Value
MER-02	0,22
MER-04	0,33
C-02 occupational	0
C-02 non-occupational	0,11
C-03 occupational fatalities	0
C-03 occupational injured	0
C-03 occupational evacuees	0
C-03 non-occupational fatalities	0,11
C-03 non-occupational injured	0
C-03 non-occupational evacuees	0

Fig. 8. RCIs available results for the natural gas explosion in Carlsbad.

Verbal-based RCIs	
Indicator	Value
MER-02	0,25
MER-04	0,43
MEE-01	0
MEE-02 non-occupational	0,57
C-02 occupational	0
C-02 non-occupational	0,57
C-03 occupational fatalities	0
C-03 occupational injured	0
C-03 occupational evacuees	0
C-03 non-occupational fatalities	0,57
C-03 non-occupational injured	0,43
C-03 non-occupational evacuees	0



Numerical-based RCIs	
Indicator	Value
MER-02	0,36
C-02 occupational	0
C-02 non-occupational	0,23
C-03 occupational fatalities	0
C-03 occupational injured	0
C-03 occupational evacuees	0
C-03 non-occupational fatalities	0,23
C-03 non-occupational injured	0,18
C-03 non-occupational evacuees	0

Fig. 9. RCIs available results for the oil explosion in Lagos.

Table 3
Comparison of the common results for the considered pipeline explosions in Carlsbad and Lagos

Indicator	Event 1: Carlsbad (Natural Gas)	Event 2: Lagos (Oil)	Comments
MER-02/verbal	0	0.25	The persistence of the release, in terms of threat, is, in both cases, higher for the oil explosion. For both events the released substance (respectively natural gas and oil) ignited and the fire lasted 55 min in Carlsbad and 12 h in Lagos
MER-02/numerical	0.22	0.36	
MER-04/verbal	0.43	0.43	No numerical-based information can be used to compare the spatial extent. From the text analyzed the extent of the damage can be classified as external, limited to the neighbourhood areas
MEE-0 1/verbal	0	0	Considering explosions, the delay of consequences is expected to be immediate, at the time of the explosion itself
C-02 occupational/verbal	0	0	The annual human mortality is referenced to the same year of the accident for both cases. From the occupational point of view no fatalities resulted from the explosion for natural gas as well as for oil. From the non-occupational side, 12 fatalities are reported for Carlsbad, and 200 for Lagos
C-02 occupational/ numerical	0	0	
C-0 2 non-occupational/ verbal	0.43	0.57	
C-02 non-occupational/ numerical	0.11	0.23	
C-03 occupational fatalities/verbal	0	0	From the occupational point of view no fatalities resulted from the explosion for natural gas as well as for oil. From the non-occupational side, 12 fatalities are reported for Carlsbad, and 200 for Lagos. The event in Lagos is also responsible for 60 injured people in non-occupational environment
C-03 occupational fatalities/numerical	0	0	
C-03 occupational injured/verbal	0	0	
C-03 occupational injured/numerical	0	0	
C-03 occupational evacuees/verbal	0	0	
C-03 occupational evacuees/numerical	0	0	
C-03 non-occupational fatalities/verbal	0.43	0.57	
C-03 non-occupational fatalities/numerical	0.11	0 0.23	
C-03 non-occupational injured/verbal	0	0.43	
C-03 non-occupational injured/numerical	0	0.18	
C-03 non-occupational evacuees/verbal	0	0	
C-03 non-occupational evacuees/numerical	0	0	

The comments group every different sub-classification of the same type of indicator.

direct involvement of the user, with his/her background, knowledge, experience, personality, etc.

Subjectivity is also evaluated within the system itself, as ERMON will use risk qualification indicators to classify the quality of information used.

As a second limit, the proposed indicators do not cover comprehensively all the aspects of risk, but are limited to what has been considered more relevant to evaluate risk in the energy sector. This is also another aspect that portrays subjectivity.

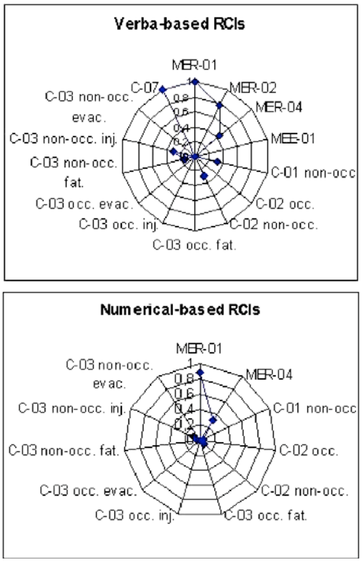
The involvement of the AHP in ranking different risk events introduces the practical limit that the number of elements involved in the comparison should not be greater than 7 ± 2 (Saaty and Ozdemir, 2003). This restriction is caused by the human limit in processing information.

It is subsequently necessary, in case the elements exceed the total amount of nine, to separate them into groups and proceed with a ranking process that is divided in different steps.

As the AHP involves directly the subjectivity of the user and is based on his/her personal judgment, the definition of the possible groups will be left to the user, who can choose to divide indicators according to different criteria (economic, environmental, etc.) related to his personal interest.

Finally, in order to complete and complement the risk panorama across the different aspects of the energy technologies, it is important to also develop a set of sustainability indicators (see, for example, IAEA et al., 2005), which addresses the positive aspects, in terms of benefits brought by the energy systems to the environmental, social, and economical dimensions of society. The idea to complement risk with sustainability aspects is discussed by Gray and Wiedemann (1999). The importance of the inclusion of sustainability-related aspects is important to the authors, as explained in Section 2.

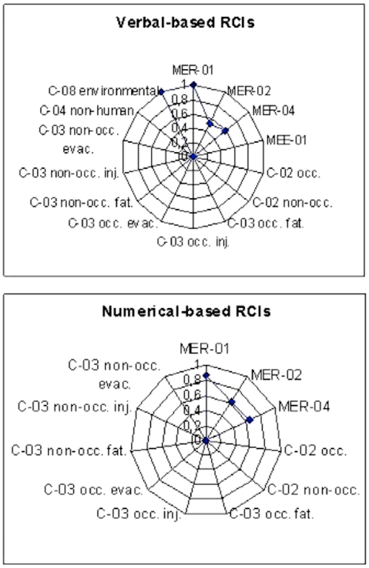
Verbal-based RCIs	
Indicator	**Value**
MER-01	1
MER-02	0,75
MER-04	0,43
MEE-01	0
C-01 non-occupational	0,29
C-02 occupational	0
C-02 non-occupational	0,29
C-03 occupational fatalities	0
C-03 occupational injured	0
C-03 occupational evacuees	0
C-03 non-occupational fatalities	0,14
C-03 non-occupational injured	0,29
C-03 non-occupational evacuees	0
C-07	1



Numerical-based RCIs	
Indicator	**Value**
MER-01	0,88
MER-04	0,32
C-01 non-occupational	0,05
C-02 occupational	0
C-02 non-occupational	0,06
C-03 occupational fatalities	0
C-03 occupational injured	0
C-03 occupational evacuees	0
C-03 non-occupational fatalities	0,03
C-03 non-occupational injured	0,1
C-03 non-occupational evacuees	0

Fig. 10. RCIs available results for the pipeline rupture and oil release in Bellingham.

Verbal-based RCIs	
Indicator	**Value**
MER-01	1
MER-02	0,5
MER-04	0,57
MEE-01	0
C-02 occupational	0
C-02 non-occupational	0
C-03 occupational fatalities	0
C-03 occupational injured	0
C-03 occupational evacuees	0
C-03 non-occupational fatalities	0
C-03 non-occupational injured	0
C-03 non-occupational evacuees	0
C-04 non-human	0
C-08 environmental	1



Numerical-based RCIs	
Indicator	**Value**
MER-01	0,85
MER-02	0,6
MER-04	0,63
C-02 occupational	0
C-02 non-occupational	0
C-03 occupational fatalities	0
C-03 occupational injured	0
C-03 occupational evacuees	0
C-03 non-occupational fatalities	0
C-03 non-occupational injured	0
C-03 non-occupational evacuees	0

Fig. 11. RCIs available results for the pipeline rupture and oil release in Chalk Point.

7. Case study

An example application of the RCIs is shown later in this section using open-source information from CNN, and from the US National Transportation Safety Board (NTSB). The considered events with their references are listed in Table 2, which highlights the link between the event under consideration and the corresponding step of the general ERMON's chain (Colli et al., 2005a). The selected events are used for two types of comparison cases:

1. *Case 1*: Comparison between two events from two different chains. Two cases of pipeline explosions are evaluated, one from the natural gas chain, and one from the oil chain.
2. *Case 2*: Comparison among three events from the same chain. Three cases of rupture and release are evaluated from the oil chain.

The events in both cases are technically similar and comparable, according to the criteria described in Section 6.

Before application, the reported information of each event has been read, evaluated, applied, and in some cases tailored to fit the indicators format.

Results are reported in table and chart format. Only indicators with a significant numerical result have been reported. Not applicable cases, where no information was found for a given indicator, were not included in the table and in the graphical representation.

In every application, the indicator(s) presenting the maximum value among those listed is (are) highlighted in the tables with a darker background of the corresponding row.

Case 1: Comparison between two events from two different chains: long distance transportation for natural gas and oil.

Events considered:

- Natural gas explosion in Carlsbad, NM, USA, 2000.
- Oil explosion in Lagos, Nigeria, 2006.

In this first application, the sources of information used are very different. Carlsbad's event is described in a detailed report from the US NTSB, while the explosion in Lagos is only reported as a piece of news, which can be quoted in one-page. Nevertheless, the information that could be extracted for use in the RCIs is good in both cases.

The application of the RCIs to the natural gas explosion in Carlsbad leads to the normalised results shown in the tables of Fig. 8, respectively, for verbal-based and numerical-based RCIs. To provide an example of graphical representation of the indicators, a radar chart is shown along with the tables.

The application of the RCIs to the oil explosion in Lagos leads to the normalised results shown in the tables of Fig. 9, respectively for verbal-based and numerical-based RCIs. As the previous case, a graphical representation of the indicators in a radar chart is shown along with the tables.

The common valid indicators to compare the two events are shown in Table 3, along with their comments.

Case 2: Comparison among three events from the same chain: regional transportation for oil.

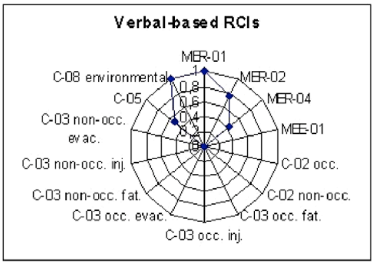
Events considered:

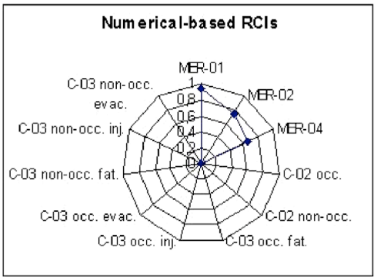
- Pipeline rupture and release in Bellingham, WA, USA, 1999.
- Pipeline rupture and release in Chalk Point, MD, USA, 2000.
- Pipeline rupture and release in Fork Shoals, SC, USA, 1996.

In this second comparison case, the source of information for the three events is the same; they are all described in detailed reports from NTSB.

Verbal-based RCIs

Indicator	Value
MER-01	1
MER-02	0,75
MER-04	0,43
MEE-01	0
C-02 occupational	0
C-02 non-occupational	0
C-03 occupational fatalities	0
C-03 occupational injured	0
C-03 occupational evacuees	0
C-03 non-occupational fatalities	0
C-03 non-occupational injured	0
C-03 non-occupational evacuees	0
C-05	0,5
C-08 environmental	1





Numerical-based RCIs

Indicator	Value
MER-01	0,94
MER-02	0,74
MER-04	0,65
C-02 occupational	0
C-02 non-occupational	0
C-03 occupational fatalities	0
C-03 occupational injured	0
C-03 occupational evacuees	0
C-03 non-occupational fatalities	0
C-03 non-occupational injured	0
C-03 non-occupational evacuees	0

Fig. 12. RCIs available results for the pipeline rupture and oil release in Fork Shoals.

Table 4
Comparison of the available results in common for the considered events

Indicator	Event 1: Bellingham	Event 2: Chalk Point	Event 3: Fork Shoals	Comments
MER-01 material/verbal	1	1	1	From the text analyzed it can be extracted that the oil release was very much above the accepted limits in all case. The order of magnitude of the release in grams is 10^8 for Bellingham and Chalk Point, and one order of magnitude more for Fork Shoals, with 10^9
MER-01 material/numerical	0.88	0.85	0.94	
MER-02/verbal	0.75	0.50	0.75	The persistence of the release can be compared only on the verbal-based information. The longest period of persistence of the threat is for Bellingham and Fork Shoals. For Chalk Point it took 40 days before the emergency was over
MER-04/verbal	0.43	0.57	0.43	The events affecting Chalk Point and Fork Shoals had the major extent, due to the contamination of water of the nearby rivers
MER-04/numerical	0.32	0.63	0.65	
MEE-01/verbal	0	0	0	The delay time between exposure and consequences can be considered immediate for all cases
C-02 occupational/verbal	0	0	0	The annual human mortality is referenced to the same year of the accident for both cases. From the occupational point of view no fatalities resulted from the release. From the non-occupational side, 3 fatalities are reported only for the event in Bellingham, 1 immediate and 2 late fatalities
C-02 occupational/numerical	0	0	0	
C-02 non-occupational/verbal	0.29	0	0	
C-02 non-occupational/numerical	0.06	0	0	
C-03 occupational fatalities/verbal	0	0	0	The only event showing presence of population immediately affected is Bellingham, which reports 1 immediate fatality and 8 injured people for non-occupational population
C-03 occupational fatalities/numerical	0	0	0	
C-03 occupational injured/verbal	0	0	0	
C-03 occupational injured/numerical	0	0	0	
C-03 occupational evacuees/verbal	0	0	0	
C-03 occupational evacuees/numerical	0	0	0	
C-03 non-occupational fatalities/verbal	0.14	0	0	
C-03 non-occupational fatalities/numerical	0.03	0	0	
C-03 non-occupational injured/verbal	0.29	0	0	
C-03 non-occupational injured/numerical	0.10	0	0	
C-03 non-occupational evacuees/verbal	0	0	0	
C-03 non-occupational evacuees/numerical	0	0	0	

Figs. 10–12 show the results for every single application of the RCIs in table and chart format. The valid results are reported for verbal-based and numerical-based indicators.

As for the previous comparison case, the common valid indicators to compare the three events are listed in Table 4, along with their comments.

The importance of the events has to be judged according to the criteria of interest from the involved person. For example, from the point of view of human consequences, Bellingham could be considered more dangerous than the other cases. On the other hand, if one were to consider the released material standpoint, Fork Shoals seems to have the highest level of threat.

8. Conclusions

The paper describes the process leading to the development of RCIs, along with the additional indicators, which will be applied in ERMON to evaluate and possibly compare incidents/accidents from different energy technologies. This method aims to provide insights to users to make better risk-informed decisions.

The authors are aware that the present level of development of the RCIs in this paper mainly addresses the consequence component of risk. The probability component will be introduced in the next stage of this PhD study in order to more completely address risk. In this work, the term risk

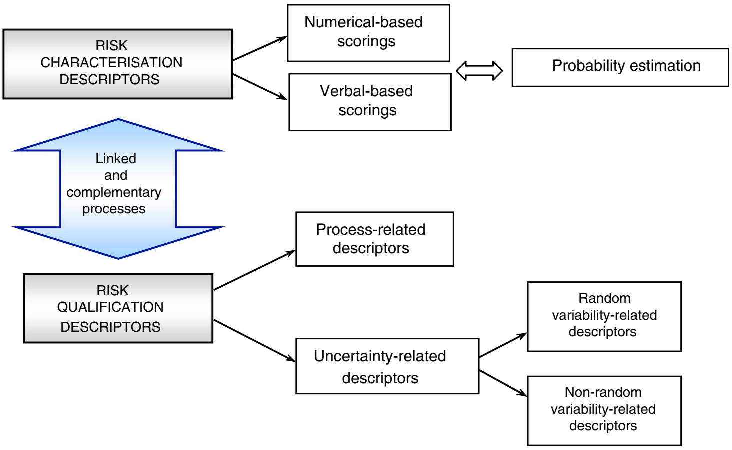


Fig. 13. Scheme showing the link among the risk characterisation and qualification methodologies as complementary processes in ERMON.

takes into consideration the wider context in which the indicators will be introduced, dealing with risk evaluation. The development has led to satisfactory results. A case study has been introduced, showing two different possibilities of comparison. It has also highlighted the fact that consequences and characteristics of events are easier to understand when expressed at the same level. The future availability of data from historical risk events from existing databases and risk assessment studies, along with information extracted from other available sources, will determine the validation of the theory and will confirm the potential of the indicators, including the comparative methodology. As the data and information collected increase, so will the possibility obtaining good statistics on incidents/accidents. In conclusion, it is important to stress that the development of the RCIs is the first phase of the ERMON methodology. The next phase will be the development of a set of risk qualification indicators (RQIs), which aim to assess the quality of the data used in ERMON (see Fig. 13 for clarification). Against this background, the NUSAP (Numerical Unit Spread Assessment Pedigree) Methodology, which defines pedigree and uncertainty matrices (Funtowicz and Ravetz, 1990), will be developed in the near future to complete the indicators development.

Acknowledgements

Particular thanks are due to Peter Burgherr (Paul Scherrer Institut, CH) and Vasilis Fthenakis (Brookhaven National Laboratory, US) for the important contribution given to the development of this work.

References

Barbir, F., Veziroglu, T.N., Plass Jr., H.J., 1990. Environmental damage due to fossil fuels use. International Journal of Hydrogen Energy 15 (10), 739–749.

CNN World News, 2006. Pipeline Explosion Kills at least 200. Posted: 2249 GMT (0649 HKT), December 26, 2006. <http://edition.cnn.com/2006/WORLD/africa/12/26/nigeria.blast/index.html>.

Colli, A., Kirchsteiger, C., 2004. Analysis of Reported Risk Figures for Natural Gas Transmission Pipelines. Safety & Regulatory Aspects, EUR 21308 EN, Publication of the European Commission Joint Research Centre, Petten, The Netherlands.

Colli, A., Vetere Arellano, A.L., Kirchsteiger, C., 2005a. Development of a General Scheme for Fuel Cycles and Life Cycles from all Energy Technologies as a Basis for the European Energy Risk Monitor (ERMON). EUR 21735 EN, Publication of the European Commission Joint Research Centre, Petten, The Netherlands.

Colli, A., Kirchsteiger, C., Vetere Arellano, A.L., Ale, B.J.M., 2005b. Methodology based on indicators for comparison of risks results from different energy systems. In: Annual Conference of the Society for Risk Analysis – Europe 2005, Major Risks Challenging Publics, Scientists and Governments, 12–14 September 2005. Politecnico di Milano-Polo di Como, Como, Italy.

Colli, A., Vetere Arellano, A.L., Kirchsteiger, C., Ale, B.J.M., in preparation. Opportunities and risks in the photovoltaic industry – the need of more information for a fair risk/benefit comparison. Safety Science.

Colli, A., Vetere Arellano, A.L., Kirchsteiger, C., 2007. ERMON's Risk Characterisation Indicators (RCIs). Publication of the European Commission Joint Research Centre, Petten, The Netherlands, EUR Report under publication during 2007.

Externe, 1997. Compiled by P. Mayerhofer, W. Krewitt, R. Friedrich, Extension of the Accounting Framework. EXTERNE Core Project, funded in part by the European Commission, with contribution from CEETA, CIEMAT, IEFE, IER, VTT, ZEW.

Fthenakis, V.M., 2001. Accident prevention and hazard management for photovoltaic manufacturing facilities. In: NCPV Program Review Meeting Proceedings, Lakewood, Colorado, 14–17 October 2001. <http://www.nrel.gov/ncpvprm/pdfs/papers/128.pdf>.

Fthenakis, V.M., Kim, H.C., Colli, A., Kirchsteiger, C., 2006. Evaluation of risks in the life cycle of photovoltaics in a comparative context. In: 21st European Photovoltaic Solar Energy Conference and Exhibition, 4–8 September 2006, Dresden, Germany.

Funtowicz, S.O., Ravetz, J.R., 1990. Uncertainty and Quality in Science for Policy. Kluwer Academic Publishers, See also: <http://www.nusap.net/>.

Gabbard, A., 1993. Coal combustion: nuclear resource or danger. ORNL Review 26 (3–4) <http://www.ornl.gov/info/ornlreview/rev26-34/text/colmain.html>.

Gray, P.C.R., Wiedemann, P.M., 1999. Risk management and sustainable development: mutual lessons from approaches to the use of indicators. Journal of Risk Research 2 (3), 201–218.

Haimes, Y.Y., 2004. Risk Modeling Assessment and Management, second ed. John Wiley & Sons Inc., ISBN 0-471-48048-7.

Hirschberg, S., Spiekerman, G., Dones, R., 1998. Project GaBE: Comprehensive Assessment of Energy Systems. Severe Accidents in the Energy Sector, first ed. Paul Scherrer Institut, ISSN-1019-0643.

Hohenemser, C., Kasperson, R.E., Kates, R.W., 1985. Causal Structure in Perilous Progress: Managing the Hazards of Technology. Westview Press, Boulder, CO.

Hohenemser, C., Kates, R.W., Slovic, P., 2000. The nature of technological hazards. In: Slovic, P. (Ed.), The perception of Risk. Risk, Society and Policy. Earthscan (Chapter 10).

International Atomic Energy Agency, UN Department of Economic and Social Affairs, International Energy Agency, Eurostat and European Environment Agency, 2005. Energy Indicators for Sustainable Development: Guidelines and Methodologies. IAEA, Vienna. <http://www-pub.iaea.org/MTCD/publications/PDF/Pub1222web.pdf>.

Kasperson, J.X., Kasperson, R.E. (Eds.), 2001. Global Environmental Risk. United Nations University Press.

National Transportation Safety Board, 2000a. Natural Gas Pipeline Rupture and Fire Near Carlsbad, New Mexico, August 19, 2000, NTSB/PAR-03/01. <http://www.ntsb.gov/publictn/2003/PAR0301.pdf>.

National Transportation Safety Board, 2000b. Rupture of Piney Point Oil Pipeline and Release of Fuel Oil Near Chalk Point, Maryland, April 7, 2000, NTSB/PAR-02/01. <http://www.ntsb.gov/publictn/2002/PAR0201.pdf>.

National Transportation Safety Board, 1999. Pipeline Rupture and Subsequent Fire in Bellingham, Washington, June 10, 1999, NTSB/PAR-02/02. <http://www.ntsb.gov/publictn/2002/PAR0202.pdf>.

National Transportation Safety Board, 1996. Pipeline Rupture and Release of Fuel Oil into the Reedy River at Fork Shoals, South Carolina, NTSB/PAR-98/01. <http://www.ntsb.gov/publictn/1998/PAR9801.pdf>.

Saaty, T.L., 1980. The Analytic Hierarchy Process: Planning Priority Setting Resource Allocation. McGraw-Hill, New York.

Saaty, T.L., Ozdemir, M.S., 2003. Why the magic number seven plus or minus two. Mathematical and Computer Modeling 38, 233–244 (with M. Ozdemir).

Scheepers, M., Seebregts, A., De Jong, J., Maters, H., 2006. EU Standards for Energy Security of Supply. Energy Research Centre of the Netherlands (ECN) and Clingendael International Energy Programme (CIEP) Publication, Report Number ECN-C-06-039/CIEP.

Stern, P.C., Fineberg, H.V. (Eds.), 1996. Understanding Risk: Informing Decisions in a Democratic Society. National Academy Press, Washington, DC.

World Nuclear Association, 2004. Naturally-Occurring Radioactive Materials (NORM). <http://www.world-nuclear.org/info/printableinformationpapers/inf30print.htm>.

Safety Science 47 (2009) 591–607

Contents lists available at ScienceDirect

Safety Science

journal homepage: www.elsevier.com/locate/ssci

Indicators to compare risk expressions, grouping, and relative ranking of risk for energy systems: Application with some accidental events from fossil fuels

A. Colli [a,*], D. Serbanescu [a], B.J.M. Ale [b]

[a] EC DG Joint Research Centre, Energy Systems Evaluation Unit, Westerduinweg 3, 1755 ZG Petten, Netherlands
[b] TU Delft, Faculty of Technology, Policy and Management, Jaffalaan 5, 2628 BX Delft, Netherlands

ARTICLE INFO

Article history:
Received 14 May 2008
Received in revised form 20 July 2008
Accepted 22 July 2008

Keywords:
Risk indicators
Risk characterisation
Relative ranking
Comparison
Fossil fuels

ABSTRACT

The comparative assessment of risk issues related to different energy systems across their steps in the fuel/life cycle is highly challenging due to the large variety of heterogeneous risk expressions, and is further complicated by the difficulty in grouping different criteria of evaluation for ranking purposes. Based on our previously developed set of 17 Risk Characterization Indicators (RCIs) to measure different risk facets, a PRA-based logic-related grouping and ranking methodology to compare and rank risks from different energy technologies is illustrated and applied. The application takes into account three fossil fuels (coal, natural gas, and oil) using selected illustrative examples in open-source form, chosen from the database ENSAD (Energy-related Severe Accident Database). The events are processed with the RCIs and ranked according the proposed methodology. The RCIs can be used either for (1) analysis of single events, (2) for comparison of events with similar characteristics, (3) for comparison of different energy technologies based on aggregated values, and (4) within Multi-Criteria Decision Analysis (MCDA) to rank events and energy chains. The benefits and limits of the energy risks comparative methodology are discussed, considering its potential to support the management of energy-related risks.

1. Introduction

This paper focuses on the validation of a set of Risk Characterisation Indicators (RCIs), which have been developed to assist in the comparison of energy risk expressions from different energy systems. Its principal aim is to demonstrate the methodology to group the RCIs and subsequently to rank events to which they are applied.

The present work brings further what already was initiated in (Colli et al., 2008), enhancing the set of RCIs with an innovative grouping and ranking approach based on PRA-related concepts and logic.

Summary information from few selected events from the ENSAD (Energy-related Severe Accident Database – continuously maintained and extended by the Paul Scherrer Institut) database is used to validate the process (Burgherr and Hirschberg, 2008; Burgherr et al., 2004; Hirschberg et al., 2004). They cover accidental events (not terrorist attacks) of significant outcomes, such as explosion/fire in fixed facilities and in pipelines, from the coal, natural gas, and oil chains, for the extraction, treatment, and regional transportation stages of the fuel cycle. The results obtained are discussed in view of the existing literature on fossil fuels.

In addition, two alternative evaluation paths for the RCIs are introduced and evaluated on the base of the same group of ENSAD cases in comparison with the main method in the paper.

To be complete, the presented methodology needs the evaluation of the quality of the process. This will be obtained through the evaluation and quantification of the uncertainty of the process, based on the contribution of the various uncertainties coming from each single step performed. This part is under development.

The paper is divided into eight sections. After the introduction, Section 2 recalls relevant information about the set of RCIs (Colli et al., 2008). Section 3 gives a theoretical description of the innovative grouping and ranking methodology. Section 4 applies the risk comparative methodology to a selected number of accidental events affecting fossil fuels extracted from the ENSAD database. Section 5 discusses the results obtained for the single steps of the fuel cycle with possibility of analysis. Section 6 shows the overall relative ranking of risks among the natural gas and the oil chains, validating the results on the base of existing literature. Section 7 presents other two evaluation paths, both based on the amount of electricity production for each of the involved coal, natural gas, and oil chains. In conclusion, general considerations are introduced, based on the validity, benefits, and limits of the methodology.

* Corresponding author. Tel.: +31 224 565027; fax: +31 224 565623.
E-mail addresses: alessandra.colli@jrc.nl (A. Colli), dan.serbanescu@jrc.nl (D. Serbanescu), b.j.m.ale@tbm.tudelft.nl (B.J.M. Ale).

0925-7535/$ - see front matter © 2008 Elsevier Ltd. All rights reserved.
doi:10.1016/j.ssci.2008.07.022

2. The Risk Characterization Indicators (RCIs)

When looking into different energy systems the basic problem is the variety of technologies encountered, the different possible hazardous situation, together with a large number of dissimilar risk expressions.

This situation calls for a general model, which could be easily adapted to different situations, and, at the same time, permits to uniform the diverse available risk information.

Such a model has been found in the approach of causal taxonomy using a causal model developed by a group of researchers (C. Hohenemser, R.E. Kasperson, R.W. Kates) at CENTED (Center for Technology, Environment and Development) at Clark University in the 1980s (Hohenemser et al., 1985). This model conceptualizes hazardous events as part of a causal sequence, beginning with a human need or want and evolving into a series of occurrences and consequences that cause harm to humans or what they value. The initial aim of this model was to help in the comparison of different technological hazards, but it was later adapted to a large number of application, including also the comparison of environmental hazards (Kasperson and Kasperson, 2001). When the backbone to understand the causal development of energy hazards is fixed, it is necessary to identify a method to highlight the characteristics of every step in a measurable way. Such a methodology is offered by C. Hohenemser, R.W. Kates and P. Slovic in their work "The nature of technological hazard" (Hohenemser et al., 2000), where they present a set of 12 indicators to characterize every step of the causal sequence, having relevant characteristics that are applicable to all types of technological hazards, comprehensible to non-experts and expressed in common units.

The choice of the causal structure has its fundamental reason in the high degree of versatility of the model, which makes it applicable to different cases and situations, in a unique identical configuration.

The analysis of the available information in energy risks, and the elaboration and refinement of the original set of indicators as from (Hohenemser et al., 2000), has led to the new modified set of RCIs as shown in Fig. 1. A total of seventeen indicators have been identified, covering the different areas of human, environmental, and economic risk. For the related classification and definitions see Table 1.

The majority of the RCIs has "general" applicability, which means that they are applicable to all the energy chains taken into account in the investigation (10 energy chains are considered: coal, natural gas, oil, nuclear, biomass, geothermal, hydro, solar photovoltaic, wind, and hydrogen as an energy carrier). Two indicators (experienced non-human mortality, and potential non-human mortality) are expected to be applicable to five energy chains (coal, oil, nuclear, hydro, and wind), while other two (latent fatalities, and trans-generational health effects) are "specific" and their applicability is mainly restricted to the coal and nuclear chains. This analysis across the specificity of the RCIs finds a partial correspondence also in the outcomes of the investigation of the possible available data and information resources for use.

These are initial evaluations with only informative significance, but the real use of the RCIs could lead to different possibilities of application.

Each RCI presents an evaluation method. The indicators can be evaluated on the basis of numerical and/or verbal statements extracted from the source of information. Both numerical-based and verbal-based evaluations are ranked according to the corresponding scales.

The characteristics of the scales are the following:

1. Verbal-based evaluation scales: all scales are based on six levels (1–6, ranked as: no significance, very low, low, moderate, high, very high), with different meaning according to what the indicator is representing (e.g. the level 4 = *moderate* could mean a time > 3 months and ⩽1 year if referred to the persistence, or a large group/up to 100 people if referred to indicators involving human beings).
2. Numerical-based evaluation scales: the definition of a quantitative scoring system for the RCIs uses the example of the basic model from (Hohenemser et al., 2000) and adopts the use of a logarithmic scale. The RCIs use a logarithmic scale on base 10. The function $\log_{10}X = Y$ presents values $Y < 0$ for $X < 1$, and values $0 \leqslant Y < 1$ for $1 \leqslant X < 10$. This has lead to the need to add the value 10 to the logarithmic argument to avoid negative results and especially to start the scale from level 1, later on needed for significance of values when applying probability theory. The scales, expressed in logarithmical form, have different upper limits according to the maximum value considered. The most of them have upper value 10, but there are also upper values 7, and 8. These circumstances lead to the introduction of a normalization process to annul the differences.

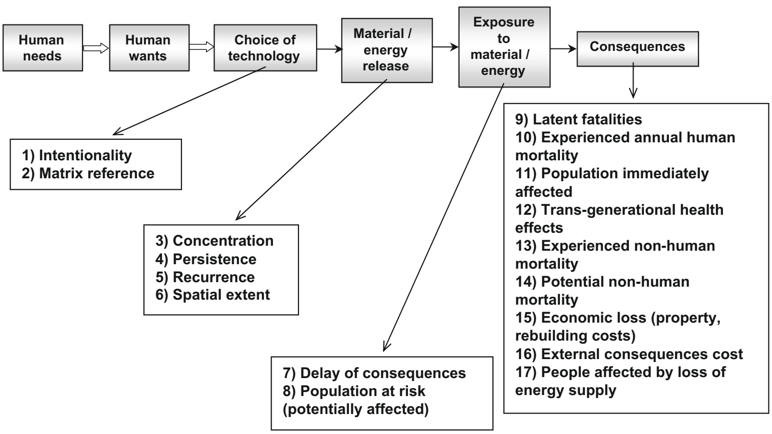


Fig. 1. Causal structure for energy systems and the linked set of RCIs.

Table 1
RCIs classification table

Step in the causal chain	Indicator identification code	Indicator	Definition	Sub-classification
Choice of technology	CT-01	Intentionality	Definition of the level of intentionality of the event into analysis, distinguishing between accidental event, external non-natural event, and normal operation	Accidental event External non-natural event Normal operation
	CT-02	Matrix reference	Identification of a fuel or life cycle in one of its main steps, or in total. It defines the element a_{ij} (energy system and step of chain) or the column (all chain) of the matrix [A] i = production, transportation, power generation, waste treatment, all j = one of the identified energy systems	Element Column
Material/energy release	MER-01	Concentration	Concentration of released energy or materials, relative to a threshold considered significant	Material Energy Nuclear radiation
	MER-02	Persistence	Time over which a release remains a significant threat to humans	
	MER-03	Recurrence	Mean time interval between releases above a minimum significant level	
	MER-04	Spatial extent	Maximum distance over which a single event has significant impact. The results are divided between internal (if not affecting areas outside the border of the involved facility or property ground) and external (with specific numerical division on the distance)	Internal External (numerical division)
Exposure to material/ energy	MEE-01	Delay of consequences	Delay time between exposure to hazard release and occurrence of consequences	
	MEE-02	Population at risk (potentially affected)	Maximum number of people potentially affected by the hazard (e.g. under worst conditions)	Occupational Non-occupational Global value (as total if the distinction is not available or clear)
Consequences	C-01	Latent fatalities	Number of people affected by latent effects. The latent fatalities are represented by the sum of late and delayed fatalities	Occupational Non-occupational Global value (as total if the distinction is not available or clear)
	C-02	Experienced annual human mortality	Average annual deaths	Occupational Non-occupational Global value (as total if the distinction is not available or clear)
	C-03	Population immediately affected	Number of immediate fatalities and/or injuries and/or evacuees in a single event	Occupational Non-occupational Global value (all with further division into: fatalities, injured, evacuees, global value as total people affected if the distinction is not available or clear)
	C-04	Trans-generational health effects	Number of human/non-human future generations at risk of adverse health effects	Human Non-human
	C-05	Experienced non-human mortality	Dead animals that have occurred	
	C-06	Potential non-human mortality	Maximum potential dead animals	
	C-07	Economical loss (property, rebuilding costs)	Property and rebuilding costs of the damaged facility	
	C-08	External consequences cost	External costs related to the event into analysis at different levels	Environmental: Impact on public and occupational health, agriculture, forests, biodiversity effects, aquatic impact, impact on materials, global impact. Non-environmental: Impact on public infrastructure, security of supply, government actions
	C-09	People affected by loss of energy supply	Number of people affected by loss/reduction of foreseen energy supply	

The indicators are applied to single events (incidents/accidents) and single pieces of information related to one or more steps along a specific energy chain (e.g. an explosion involving a natural gas pipeline for the first and a report concerning threats of nuclear energy in the latter). Different analogous applications of the risk indicators allow a cross comparison among the chosen events and steps of the chain. Comparison among energy chains will be allowed as a final outcome of a large number of gathered information, otherwise it must be stated that the outcome is dependent from the cases and the steps of the chain considered.

To avoid inconsistencies, the comparison of two or more events should follow specific criteria:

- The events should be related to the same level of the fuel or life cycle under consideration, or, at least, they should take into consideration similar processes.

- The events should be 'technically' similar (e.g. comparison of different explosions concerning natural gas and oil).
- The indicators adopted for the comparison should have been evaluated for all the events analysed. If information on one indicator has been provided for only some events, but not for some others, then this indicator should be excluded from the comparative process.
- If possible, the original format of the information can be used for a given indicator; however, it may be the case that information needs to be elaborated or interpreted before being used.

It is not necessary to have information for all the indicators for every event analysed, but the higher the number of indicators available for the comparison, the more complete the information and the outcome will be.

It must be stressed that this set of RCIs is one possible set of indicators to characterize energy risks. The set can be modified if necessary, but the grouping and ranking methodology that follows will not be affected and is generally valid.

3. Grouping and ranking method for the RCIs using a PRA-based methodology

The proposed method to compare energy risks does not consist only in the application of the set of RCIs, but includes also the various steps shown in Fig. 2. In this visual representation of the process, it can immediately be seen that the application of the RCIs is only the first among thirteen steps to reach the final relative ranking of the observed events. In view of a possible future development of a tool based on this methodology, all the steps should be performed and managed by a team of experts to reduce the impact of human factors in the process (such as different models or evaluations set by different users with different background), and a peer-review procedure should be considered. Only the final results are shown to the public.

As highlighted in (Colli et al., 2008) and stated also in the previous Section 2, the indicators adopted in the comparative process should have an evaluation (different from NA = not applicable) for all the events into analysis. This is necessary for the significance of the comparison itself. Thus, in step 2 the appropriate indicators are selected to be processed in the following steps.

Another problem related to the differences in the evaluation scale is that the resulting values obtained by the initial application of the indicators could be inhomogeneous according to the scales, which could have different upper limits. Numerical-based applications of the RCIs have scales mostly 1–10, but few indicators have scales 1–7 and 1–8. To avoid inconsistency in the comparison and reach homogeneous numbers, the values are normalized in two steps.

When comparing different events on the base of some selected criteria, the result is shown in a matrix-like form, where every column corresponds to a selected event, and each row to a comparison criterion. Thus, having a set on N events evaluated on a set of M criteria, the matrix appears as follows:

$$[I] = \begin{bmatrix} I_{1A} & I_{1B} & I_{1C} & \cdots & I_{1N} \\ I_{2A} & I_{2B} & I_{2C} & \cdots & I_{2N} \\ I_{3A} & I_{3B} & I_{3C} & \cdots & I_{3N} \\ \cdots & \cdots & \cdots & \cdots & \cdots \\ I_{MA} & I_{MB} & I_{MC} & \cdots & I_{MN} \end{bmatrix}. \tag{3.1}$$

The 2-step normalization process first shows that every result is divided by the maximum of its associated scale (row-based). Secondly, each value is normalized to the sum of all values in the corresponding column.

The problem of different upper scale limits involves only the RCIs with numerical-based application, as the verbal-based one follows scales all in the range 1–6. Anyhow, to ensure the parallel approach for both methods the 2-steps normalization is executed also for the verbal-based evaluation.

The RCIs want to express risk as a combination of consequences and probabilities. The consequences are clearly evaluated through the application of the indicators with their scales. In fact, the RCIs have been developed from a previous set of indicators used to evaluate all types of technological hazards (Hohenemser et al., 2000). Their evaluation is actually a hazard characterization and quantification. But talking about risk values means that hazards and probabilities are both considered, according to the definition of risk adopted in this work.

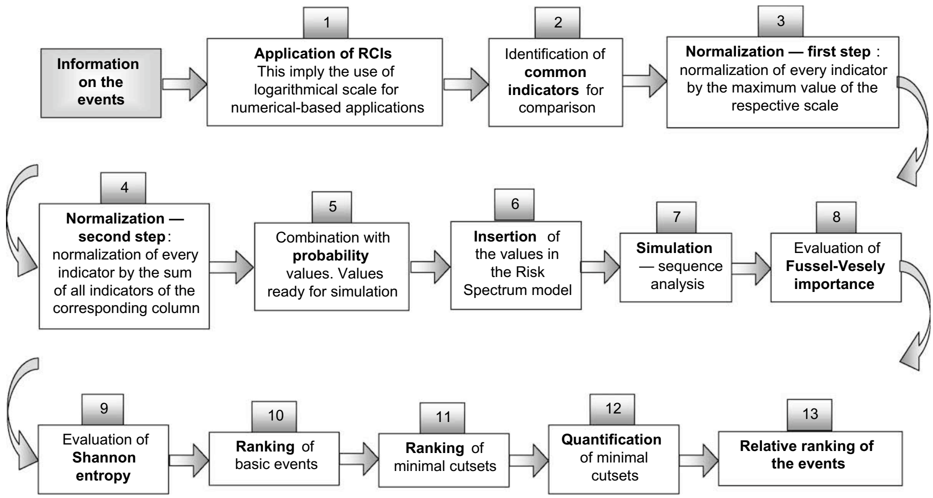


Fig. 2. Step-by-step explanation of the process starting from the application of the RCIs to selected events, and leading to the relative risk ranking of the events themselves.

In some cases it could be said that the probability has been considered in the study behind the data processed in the RCIs application. But it is not always sure and verifiable. In this context it is better to define and include in the indicators our calculated probabilities. Finding information about probabilities considering a specific event in a specific fuel or life cycle is difficult or almost impossible in some cases (e.g. new technologies and renewable energies). And where possible, it is based on statistical information not easy to obtain. To avoid this problem, it can be assumed that the information collected to sustain the application of the methodology in its completed final version will be used also as a support to define probabilities. In fact, when practically applied in the form of a tool, the methodology needs to rely on a consistent database; this database, when established, will offer also the necessary background on which the application of the Bayes theorem is possible, reaching the identification of the posterior distribution of probability for selected cases. In the context of this paper, when performing the practical application using selected events from fossil fuels, specific assumption for probability are introduced.

Once the proper values are obtained, they are introduced in the developed model and processed through the use of RiskSpectrum® PSA Professional (© Relcon Scandpower AB, 2008), a simulation software for fault tree and event tree analysis widely used at nuclear power plants. The process of building the model starts by identifying, according to each step of the causal chain, the possible links among the corresponding indicators, some of which are independent, and some are dependent to other(s). For each stage of the causal chain the associations are:

- *Choice of technology:* the two indicators, intentionality and matrix reference, are considered as possibly independent.
- *Material/energy release:* the two indicators, persistence and recurrence, are considered as possibly independent. The other two indicators, concentration and spatial extent, are considered as possibly dependent.
- *Exposure to material/energy:* the two indicators, delay of consequences and population at risk, are considered as possibly independent.
- *Consequences*: the relations among the indicators of this step of the causal chain are shown in Fig. 3, where the only possibly independent indicator is C-07 – economic loss, in terms of property and rebuilding costs. The other indicators are considered as possibly dependent according to the links shown in Fig. 3.

Once defined, these links are then visualized in form of a fault tree, connected to the steps of the causal chain, which are transferred into the function events of the connected event tree (using Probabilistic Risk Analysis (PRA) visualization). Every fault tree is a logical model which links the RCIs to the correspondent step in the causal chain.

For the need of the model and the simulation, an additional fault tree represent the input event has been added to those linked to the causal chain; this tree is linked to the initiating event of the event tree.

The model for simulation is built for the complete set of indicators, and remains the same once the interdependencies among the RCIs are set. Then, each case undergoes the simulation with only the basic events corresponding to the indicators with available information. The non useful branches of the trees are switched off, or, where necessary, deleted from the model, allowing an adaptation to each single case.

Once the model is ready for simulation with the appropriate values, it is processed for sequence analysis with Risk Spectrum and the results concerning the importance of the basic events, and the list of minimal cutsets are taken into consideration. The sequence analysis of the model leads to define the importance of every basic event, equivalent to a specific indicator. The importance of the basic events is calculated in Risk Spectrum with different approaches. The one considered for our study is based on the Fussell–Vesely formula, giving the importance as the ratio between the top event unavailability based only on all the minimal cutsets (MCSs) where the basic event '*i*' is included, and the top event unavailability including all minimal cutsets:

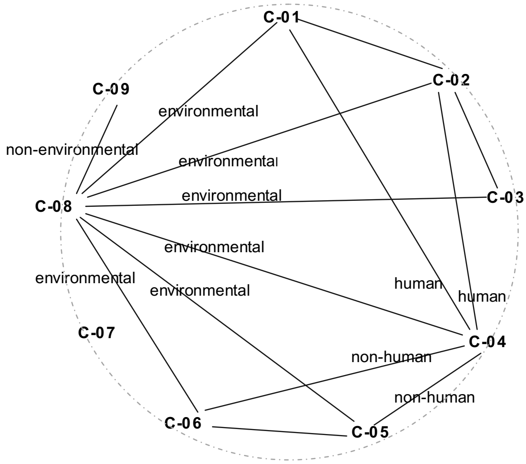


Fig. 3. Diagram showing the possible links among the indicators of the *consequences* step in the causal chain. These links are translated into possible sets of combinations, useful for the transfer into the fault-tree-like model. The indicators are represented with their identification codes, according to the list in Table 1.

$$I_i^{FV} = \frac{Q_{TOP}(MCS_{including(i)})}{Q_{TOP}}. \quad (3.2)$$

The importance according to Fussell–Vesely, together with the value assigned in the model, is processed using the Shannon formula, to reach the ranking of the basic events. Shannon developed an entropy formula, based on the statistical thermodynamics formulation of entropy, to assess the level of disorder in the transmission of signals. On the basis of this formula he could define the number of bits to be transmitted in a specific signal (Shannon, 1948). This formula can be adapted also to the probabilistic environment (Jaynes, 2003). The ranking of the basic events of the model is made according to the absolute value resulting from the Shannon entropy formula in the following form (Serbanescu, 1991):

$$|H| = |\,\omega_i q_i \cdot \ln(\omega_i q_i)|. \quad (3.3)$$

The Fussell–Vesely importance is treated by the Shannon formula as a weighting factor for the definition of the ranking, and it is identified by the term ω_i. The term q_i represents the unavailability according to the definition adopted in the Risk Spectrum program, and refers to the values inserted in the model for the simulation, which match with probabilities. Once obtained the ranking of the basic events, it is possible to proceed to identify the ranking of the minimal cutsets.

This ranking process allows the identification of groups of basic events and minimal cutsets. Thus, the indicators and their possible combinations are grouped according to their importance and entropy level.

Finally, the quantification of the minimal cutsets and their overall value gives the ranking of the event into analysis. After processing all events with this approach, the most significant event is highlighted, and all the others are relatively ranked in its comparison.

It must be stressed that the verbal-based and the numerical-based RCIs are processed separately along all the application, up to the final ranking, to avoid inconsistencies due to the different evaluation methods.

4. Application of the RCIs using selected fossil fuels accidental cases

The theoretical development of the RCIs and the relative ranking method needs to be evaluated with a practical application. Throughout this paper, an application is shown for fossil fuels. A representative sample of cases has been selected and extracted from the ENSAD database, maintained by the Paul Scherrer Institut (PSI, Switzerland) (Burgherr and Hirschberg, 2008; Burgherr et al., 2004; Hirschberg et al., 1998) to demonstrate the application of the RCIs.

The first choice of the possible applicable cases relies on the following criteria:

- *Events*: accidental cases from coal, natural gas, and oil, with the intent to cover the most possible steps in the general chain proposed in Table 2.
- *Place of the events:* OECD countries.
- *Time frame:* period 1969–2000.
- *Severity*: most severe accidents to extent feasible, i.e. if some others with a similar magnitude of consequences provide more and detailed information there should be flexibility in the choice. The focus is on high impact events for the importance attributed to extreme events (Haimes, 2004).

Nevertheless, small accidents are also important contributors and the authors are aware of that.

Concerning the presence of cases along the fuel cycle, the only restriction applies to coal, where practically no severe accidents occurred in other steps than extraction (part of production).

The cases identified by this first selection procedure undergo a second selection, according to additional comparison criteria (comparable events should be technically similar and allow comparison among at least two chains). Thus the restriction only to fire and explosion cases among those available.

The selected cases are then identified by a reference code for convenience; the code shows the link to the fuel cycle (C = coal, NG = natural gas, O = oil) and lists the cases by number (see Table 2).

The cases are used for application with the RCIs according to the procedure previously exposed in Section 3, reaching the relative risk ranking of the events. An overview of the application's phases is also shown in Fig. 4.

The two configurations of the RCIs (verbal-based and numerical-based), are processed separately for convenience and meaning of the results.

The procedure is repeated up to the final ranking for the three steps which make possible a cross comparison among the involved fossil chains (Table 2). The steps are:

1. Extraction.
2. Treatment.
3. Regional transportation.

The extraction step is the only one which allows comparison among the three fossil chains.

Even if there is a restriction of the steps of the fuel cycle involved in this case study due to the criteria of event selection, accidents happen at every stage of the chain and no step can be considered as totally risk free.

Finally, taking into account the majority of accidents included in ENSAD for the selected period of time, the events are evaluated as energy-related according to the ENSAD-related definition (Burgherr et al., 2004; Hirschberg et al., 1998).

4.1. Application of the RCIs and normalization of results

When applying the RCIs to the selected cases, the first step is to identify which information is available in verbal form, and which

Table 2
Considered accidental cases, linked to the related steps in the general chain developed to fit different fuel/life cycles (Colli et al., 2005)

Main step	Sub-step of first level	Sub-step of second level	Coal	Natural gas	Oil
Production	Exploration				
	Extraction		Explosion/fire in fixed facilities (6) – Reference C-1 to C-6	Explosion in fixed facilities (3) and pipeline explosion on platform (1) – Reference NG-1 to NG-4	Explosion/fire in fixed facilities (2) – Reference O-1 and O-2
	Treatment			Explosion/fire in fixed facilities (1) – Reference NG-5	Explosion/fire in fixed facilities (3) and pipeline explosion in refinery (1) – Reference O-3 to O-6
Transportation	Raw material transportation				
	Transportation	Long distance			
		Regional		Pipeline explosion (3) – Reference NG-6 to NG-8	Explosion on ship (2) – Reference O-7 and O-8
		Local			
	Waste transportation				
	Storage	Material storage			
		Waste storage			
Power generation	Fixed installation	Construction			
		Operation			
		Dismantling			
	Transmission/distribution facilities				
Waste treatment	Waste reprocessing				
	Waste disposal				

The general chain has four main steps, subsequently divided into more detailed sub-steps of first and second level.

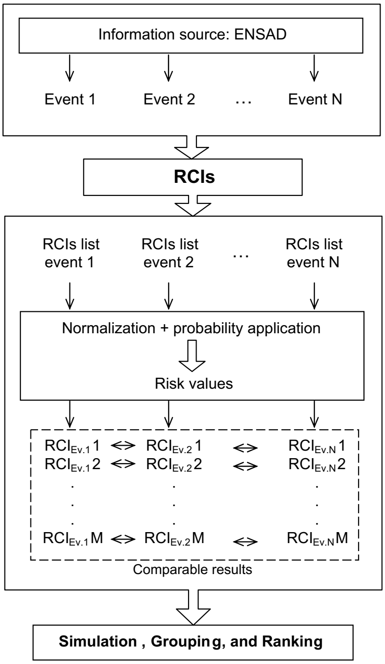


Fig. 4. Application procedure of the RCIs. They will be applied to single events with inhomogeneous information, to reach comparable risk results and overall ranking.

in numerical form. Then the verbal-based and the numerical-based applications are carried on in parallel, based on the different scales previously introduced.

In the next three subsections the normalized values of the verbal-based and the numerical-based applications off the RCIs included in the comparison are shown, respectively in Tables 3 and 4 for extraction, Tables 5 and 6 for treatment, and Tables 7 and 8 for regional transportation. As previously described, the normalization is processed according to two steps. The first one involves the normalization of each row according to the maximum value of the applied scale of the correspondent indicator. In this example, and considering only the RCIs available for comparison, the upper scale value is 6 for the verbal-based RCIs, and 10 for the numerical-based RCIs involved in this comparison (C-02 and C-03).

The second step involves the normalization of each value according to the sum of the corresponding column.

4.1.1. Extraction

See Tables 3 and 4.

4.1.2. Treatment

See Tables 5 and 6.

4.1.3. Regional transportation

See Tables 7 and 8.

4.2. Grouping and relative ranking

Once the normalized values are obtained, the process enters in the probability evaluation and composition (step 5 as from Fig. 2). For this purpose and due to the fact that reliable probability data for the events involved were not available for this study, let's consider the frequency of the events. It is considered that every event has frequency 1. It happened at least once, thus frequency is 1. Meaning that frequency 1, the event exists, suggests also that the probability is 1. Thus, all the normalized values are assumed to be multiplied by 1. With this supposition, it is possible to say that the normalized results are proportional, thus correspondent, to the probability values. This simple assumption makes it possible to use the normalized values from the RCIs application as probabilities in the developed PRA-based model and its subsequent Risk Spectrum simulation. Through the simulation it is possible to assess the combinations of the indicators, and the ranking of the events.

The Risk Spectrum simulation software is normally used with low probabilities (order of 10^{-2} or lower). With the present application the program has to deal with high probability values, thus limitations have to be expected. When assuming probability 1, a subjective probability is taken into account.

Table 3
Normalized results for the verbal-based RCIs

	Verbal-based RCIs												
Chain	Coal						Natural gas				Oil		Comments
Case	C-1	C-2	C-3	C-4	C-5	C-6	NG-1	NG-2	NG-3	NG-4	O-1	O-2	
Indicator													
MER-04	0.20	0.20	0.20	0.23	0.23	0.23	0.25	0.23	0.27	0.27	0.25	0.23	The spatial extent is internal/extended for all cases, but O-1, which has been classified as external/limited to 1 country as the information said about release to the surrounding, with later explosion, fire, and blowout off the coast of Scotland
C-02, global	**0.33**	**0.33**	**0.33**	0.31	0.31	0.31	0.25	0.23	0.18	0.18	0.31	0.31	The experienced annual human mortality has the highest rates among coal and oil cases
C-03, global, fatalities	**0.33**	**0.33**	**0.33**	0.31	0.31	0.31	0.25	0.23	0.18	0.18	0.31	0.31	The highest rate of fatalities can be counted for coal and oil cases
C-03, global, injured	0.07	0.07	0.07	0.08	0.08	0.08	0.17	0.23	0.27	0.27	0.06	0.08	Coal and oil cases present no injured. The only injured people are reported for natural gas cases
C-03, global, evacuees	0.07	0.07	0.07	0.08	0.08	0.08	0.08	0.08	0.09	0.09	0.06	0.08	No evacuees in all cases

The highest value is highlighted in bold characters. The comments based on the original information are in the corresponding column.

Table 4
Normalized results for the numerical-based RCIs

Chain	Numerical-based RCIs: Coal						Natural gas				Oil		Comments
Case	C-1	C-2	C-3	C-4	C-5	C-6	NG-1	NG-2	NG-3	NG-4	O-1	O-2	
Indicator													
C-02, global	**0.36**	0.35	0.34	0.33	0.33	0.33	0.27	0.26	0.25	0.26	0.35	0.32	The experienced annual human mortality has the highest rates among coal and oil cases
C-03, global, fatalities	**0.36**	0.35	0.34	0.33	0.33	0.33	0.27	0.26	0.25	0.26	0.35	0.32	The highest rate of fatalities can be counted for coal and oil cases
C-03, global, injured	0.14	0.15	0.16	0.17	0.17	0.17	0.25	0.26	0.28	0.26	0.15	0.18	Coal and oil cases present no injured. The only injured people are reported for natural gas cases, respectively 4, 6, 11, and 6 people
C-03, global, evacuees	0.14	0.15	0.16	0.17	0.17	0.17	0.21	0.21	0.21	0.22	0.15	0.18	No evacuees in all cases

The highest value is highlighted in bold characters. The comments based on the original information are in the corresponding column.

Table 5
Normalized results for the verbal-based RCIs

Chain	Verbal-based RCIs: Natural gas	Oil				Comments
Case	NG-5	O-3	O-4	O-5	O-6	
Indicator						
MER-04	0.30	0.27	0.30	0.20	0.30	The spatial extent is classified as internal/extended for all cases
C-02, global	0.30	0.27	0.30	0.20	0.30	The rate of annual human mortality is classified as affecting always a small group/up to 50 people in all cases
C-03, global, fatalities	0.30	0.27	0.30	0.20	0.30	The rate of annual human mortality is classified as affecting always a small group/up to 50 people in all cases
C-03, global, evacuees	0.10	0.18	0.10	**0.40**	0.10	Three cases have no evacuees (rate 1), while the case O-5 have the highest rate (6 = very high = country level/population of one or more countries/>1000 people), involving 10,000 people

The highest value is highlighted in bold characters. The comments based on the original information are in the corresponding column.

Table 6
Normalized results for the numerical-based RCIs

Chain	Numerical-based RCIs: Natural gas	Oil				Comments
Case	NG-5	O-3	O-4	O-5	O-6	
Indicator						
C-02, global	0.35	0.38	0.37	0.20	0.36	The global fatalities counted in the annual human mortality are in order: 6, 37, 13, 12, and 10. The lowest value is shown by the natural gas case
C-03, global, fatalities	0.35	0.38	0.37	0.20	0.36	The global fatalities counted in the annual human mortality are in order: 6, 37, 13, 12, and 10. The lowest value is shown by the natural gas case
C-03, global, evacuees	0.29	0.24	0.27	**0.60**	0.28	Three cases have no evacuees (rate 1), while the case O-5 involves the highest number of evacuees, affecting 10,000 people

The highest value is highlighted in bold characters. The comments based on the original information are in the corresponding column.

Table 7
Normalized results for the verbal-based RCIs

Chain	Verbal-based RCIs: Natural gas			Oil		Comments
Case	NG-6	NG-7	NG-8	O-7	O-8	
Indicator						
MER-04	0.31	0.25	0.22	**0.33**	**0.33**	In most cases the spatial extent is evaluated as moderate, external. Only in case NG-7 the rate is low, for internal/extended
C-02, global	0.23	0.25	0.22	0.25	0.25	In most cases the rate is 3 = low = small group/up to 50 people. Only case NG-8 have rate 4 = moderate = large group/up to 100 people.
C-03, global, fatalities	0,23	0,25	0,22	0,25	0,25	In most cases the rate is 3 = low = small group/up to 50 people. Only case NG-8 have rate 4 = moderate = large group/up to 100 people
C-03, global, injured	0.15	0.17	0.28	0.08	0.08	Only natural gas cases have injured people, while no one is affected in the two oil cases. The highest rate is shown by case NG-8
C-03, global, evacuees	0.08	0.08	0.06	0.08	0.08	No evacuees in all cases

The highest value is highlighted in bold characters. The comments based on the original information are in the corresponding column.

Table 8
Normalized results for the numerical-based RCIs

	Numerical-based RCIs					
Chain	Natural gas			Oil		Comments
Case	NG-6	NG-7	NG-8	O-7	O-8	
Indicator						
C-02, global	0.27	0.26	0.26	0.31	0.30	The information is available for all the interested cases, involving respectively 8, 6, 92, 29, and 26 people
C-03, global, fatalities	0.27	0.26	0.26	0.31	0.30	The information is available for all the interested cases, involving respectively 8, 6, 92, 29, and 26 people
C-03, global, injured	0.24	0.25	0.34	0.19	0.20	Only natural gas cases have injured people, while no one is affected in the two oil cases. The number of people for NG cases is respectively 3, 4, and 425
C-03, global, evacuees	0.22	0.22	0.13	0.19	0.20	No evacuees in all cases

The comments based on the original information are in the corresponding column.

In Risk Spectrum the link between frequency and probability is given by:

$$W(t) = \lambda(1 - Q(t)), \qquad (4.2.1)$$

where $W(t)$ is the unconditional failure intensity (frequency), $Q(t)$ is the unavailability (probability), and λ is the failure rate. When fixing the frequency as 1, and thus the correspondent probability as 1, there must be a failure rate λ with high value, to turn the term $1/\lambda$ to an almost negligible value. This means that assuming a high subjective probability, implies the assumption of a high failure rate.

The limitations of Risk Spectrum arise when dealing with such a context, where combinations of scenarios for decision purposes are involved. These limitations lead to results which have significance only for relative ranking purposes and have to be evaluated in a relative comparison among each event taken into consideration.

Nevertheless, the logic of the process and of the all system is not touched, and remains valid for the purpose of this work.

The values in Tables 3–8 are assumed multiplied by 1 and proportional to probabilities. Event by event, for the two parallel verbal-based and numerical-based applications, those values can now be inserted in the model built establishing the links among the RCIs. These applications shown in the next three subsections lead first to the grouping and ranking of the indicators (basic events of the model). Once the taxonomy of the basic events is obtained, it is possible to establish the grouping and ranking of the combinations of the RCIs (the minimal cutsets of the model).

Finally, the ranking of the events for each of the three fuel cycle steps into exam is reached, based on the combination of the values of the minimal cutsets.

Overall average values useful for comparison among the chains are also obtained.

It must be stressed that the final ranking of the events is first of all dependent on the number and the characteristics of the events considered, and in a second stage is a relative ranking, which means that the importance of the events and the overall average importance must be related to the maximum value among those presently obtained.

4.2.1. Extraction

The grouping procedure for the verbal-based and numerical-based extraction cases relies on the model based on the fault trees shown in Figs. 5–8.

The application is done per single event, considering the values of Tables 3 and 4, plus the following additional basic events assumed with probability = 1:

- Event, referred to the input event into consideration.
- Accidental event, referred to the intentionality indicator.
- Element, referred to the matrix reference indicator.

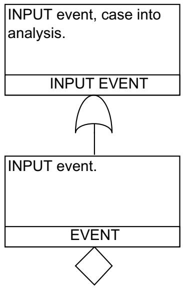


Fig. 5. Tree representing the input event, which is represented by a basic event that could be further developed (diamond symbol). The presence of an OR gate with one basic event is allowed and does not imply any distortion in the minimal cutsets.

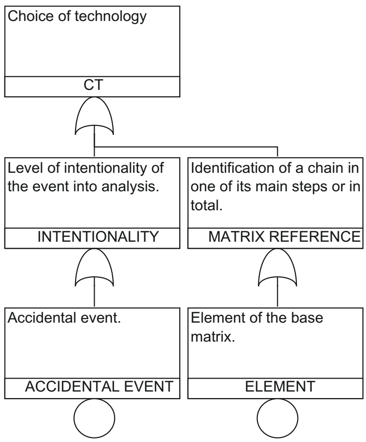


Fig. 6. Tree representing the step 'choice of technology' with the only indicators involved in this comparison case. The indicators intentionality and matrix reference are represented respectively by the basic events 'accidental event' and 'element'. In this paper only accidental events are considered.

Processing the simulation and considering the Fussell–Vesely importance according to the process previously discussed, the ranking of the basic events is obtained, respectively, for the verbal-based and numerical-based application of the RCIs. Applying

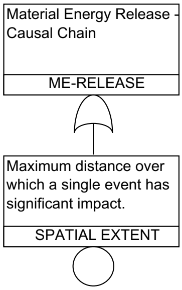


Fig. 7. Tree representing the step 'material/energy release' with the only indicator involved in this comparison case, spatial extent. The indicators not involved, and for which there are no significant values, are not shown in this tree. The presence of an OR gate with one basic event is allowed and does not imply any distortion in the minimal cutsets.

this taxonomy to the minimal cutsets, three groups of possible cutsets are defined (H, M, and L, see Tables 9 and 11), which give the ranking of the combinations of RCIs. In both verbal-based and numerical-based rankings, the combinations with the highest importance are those including the indicator C-03 (population immediately affected) in its sub-classification including the number of global fatalities.

For each group of minimal cutsets a risk value is calculated in correspondence to every single case considered. Combining the values of the three groups, the total risk value for each case is calculated (see Tables 10 and 12).

In the verbal-based application the highest ranking value is shown by event O-1, while in the numerical-based application the event C-1 shows the highest ranking value. These are considered dominant events from the risk point of view.

Having done a risk ranking for all selected events, it is now possible to reach the average values corresponding to the risk of the specific fuel cycle. For better understanding, the values are converted into a ranking level, which classifies the chains from highest (I) to lowest (III) level of risk (see Table 13). This classification is obviously dependent on the events under analysis, on their number, and their characteristics.

4.2.2. Treatment

The fault trees and their assumptions in the treatment stage are the same as in the extraction case, with the only exception that the consequences tree does not show the global value of injured for the indicator C-03.

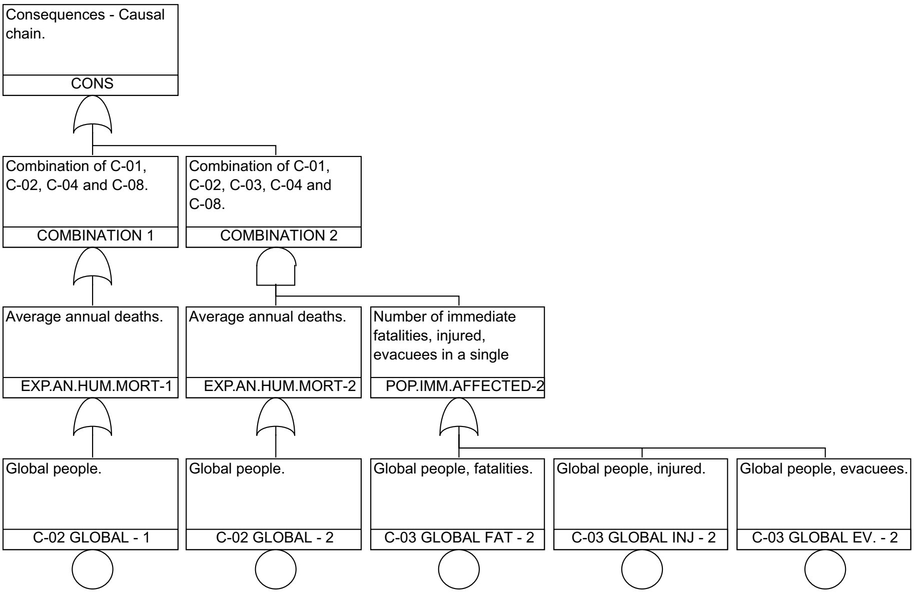


Fig. 8. Simplified representation of the 'consequences' tree for the only indicators involved in the comparison case, here shown as basic events.

Table 9
Ranking of the importance of the minimal cutsets for the verbal-based application, based on the importance of the involved basic events (indicators)

Combinations/grouping of indicators and respective relative ranking (extraction – verbal-based)					
ACCIDENTAL EVENT	C-02 GLOBAL - 1	EVENT	SPATIAL EXTENT		L
C-02 GLOBAL - 1	ELEMENT	EVENT	SPATIAL EXTENT		L
C-02 GLOBAL - 2	C-03 GLOBAL FAT - 2	ELEMENT	EVENT	SPATIAL EXTENT	H
ACCIDENTAL EVENT	C-02 GLOBAL - 2	C-03 GLOBAL FAT - 2	EVENT	SPATIAL EXTENT	H
C-02 GLOBAL - 2	C-03 GLOBAL INJ - 2	ELEMENT	EVENT	SPATIAL EXTENT	M
ACCIDENTAL EVENT	C-02 GLOBAL - 2	C-03 GLOBAL EV. - 2	EVENT	SPATIAL EXTENT	M
C-02 GLOBAL - 2	C-03 GLOBAL EV. - 2	ELEMENT	EVENT	SPATIAL EXTENT	M
ACCIDENTAL EVENT	C-02 GLOBAL - 2	C-03 GLOBAL INJ - 2	EVENT	SPATIAL EXTENT	M

Table 10
Risk ranking of the minimal cutsets grouping for the verbal-based application, reaching a total risk value for every event into analysis

	Extraction – Verbal-based RCIs											
	Coal						Natural gas				Oil	
	C-1	C-2	C-3	C-4	C-5	C-6	NG-1	NG-2	NG-3	NG-4	O-1	O-2
H	0.04	0.04	0.04	0.04	0.04	0.04	0.03	0.02	0.02	0.02	0.05	0.04
M	0.02	0.02	0.02	0.02	0.02	0.02	0.03	0.03	0.04	0.04	0.02	0.02
L	0.13	0.13	0.13	0.14	0.14	0.14	0.13	0.11	0.10	0.10	0.16	0.14
	Total											
	0.20	0.20	0.20	0.21	0.21	0.21	0.19	0.16	0.15	0.15	**0.22**	0.21

Table 11
Ranking of the importance of the minimal cutsets for the numerical-based application, based on the importance of the involved basic events (indicators)

Combinations/grouping of indicators and respective relative ranking (extraction – numerical-based)				
ACCIDENTAL EVENT	C-02 GLOBAL – 1	EVENT		L
C-02 GLOBAL – 1	ELEMENT	EVENT		L
C-02 GLOBAL – 2	C-03 GLOBAL FAT - 2	ELEMENT	EVENT	H
ACCIDENTAL EVENT	C-02 GLOBAL - 2	C-03 GLOBAL FAT - 2	EVENT	H
C-02 GLOBAL – 2	C-03 GLOBAL INJ - 2	ELEMENT	EVENT	M
ACCIDENTAL EVENT	C-02 GLOBAL - 2	C-03 GLOBAL EV. - 2	EVENT	M
C-02 GLOBAL - 2	C-03 GLOBAL EV. - 2	ELEMENT	EVENT	M
ACCIDENTAL EVENT	C-02 GLOBAL - 2	C-03 GLOBAL INJ - 2	EVENT	M

Table 12
Risk ranking of the minimal cutsets grouping for the numerical-based application, reaching a total risk value for every event into analysis

	Extraction – numerical-based RCIs											
	Coal						Natural gas				Oil	
	C-1	C-2	C-3	C-4	C-5	C-6	NG-1	NG-2	NG-3	NG-4	O-1	O-2
H	0.25	0.24	0.23	0.22	0.21	0.21	0.15	0.14	0.13	0.13	0.24	0.21
M	0.21	0.21	0.22	0.22	0.23	0.23	0.25	0.25	0.25	0.25	0.21	0.23
L	0.71	0.69	0.67	0.66	0.65	0.65	0.54	0.53	0.50	0.52	0.69	0.64
	Total											
	1.17	1.15	1.12	1.11	1.09	1.09	0.93	0.92	0.88	0.90	1.14	1.08

Table 13
Levels of risk in extraction, dependent on the considered cases into analysis

Average values of risk in extraction			
	C	NG	O
Verbal-based application	II	III	I
Numerical-based application	I	III	II

The simulation is carried on per single event, considering the values of Tables 5 and 6.

Three groups of possible cutsets are identified for verbal-based application (H, M, and L, see Table 14), and two (H and L, see Table 16) for numerical-based application, in both cases following the same criteria of definition.

The combination of RCIs (minimal cutsets) with the highest importance include the indicator C-03 (population immediately affected) in its sub-classification including fatalities for the verbal-based applications. On the other hand, the numerical-based applications include also the sub-classification of evacuees, taking into consideration all the divisions in which C-03 appears in the model for this specific case study.

For each group of minimal cutsets a risk value is calculated in correspondence to every single considered case. Combining the values of the three groups, the total risk value for each case is calculated (see Tables 15 and 17).

The relative ranking of the events shows different dominances in the verbal-based application compared to the numerical-based one. In the first approach the dominant events from the risk point of view are NG-5, O-4 and O-6. In the second approach the

Table 14
Ranking of the importance of the minimal cutsets for the verbal-based application, based on the importance of the involved basic events (indicators)

Combinations/grouping of indicators and respective relative ranking (treatment – verbal-based)					
C-02 GLOBAL – 1	ELEMENT	EVENT	SPATIAL EXTENT		L
ACCIDENTAL EVENT	C-02 GLOBAL – 1	EVENT	SPATIAL EXTENT		L
C-02 GLOBAL – 2	C-03 GLOBAL FAT - 2	ELEMENT	EVENT	SPATIAL EXTENT	H
ACCIDENTAL EVENT	C-02 GLOBAL – 2	C-03 GLOBAL FAT - 2	EVENT	SPATIAL EXTENT	H
C-02 GLOBAL – 2	C-03 GLOBAL EV. – 2	ELEMENT	EVENT	SPATIAL EXTENT	M
ACCIDENTAL EVENT	C-02 GLOBAL – 2	C-03 GLOBAL EV. - 2	EVENT	SPATIAL EXTENT	M

Table 15
Risk ranking of the minimal cutsets grouping for the verbal-based application, reaching a total risk value for every event into analysis

	Treatment – verbal-based RCIs				
	Natural gas	Oil			
	NG-5	O-3	O-4	O-5	O-6
H	0.05	0.04	0.05	0.02	0.05
M	0.02	0.03	0.02	0.03	0.02
L	0.18	0.15	0.18	0.08	0.18
	Total				
	0.25	0.22	**0.25**	0.13	**0.25**

Table 16
Ranking of the importance of the minimal cutsets for the numerical-based application, based on the importance of the involved basic events (indicators)

Combinations/grouping of indicators and respective relative ranking (treatment – numerical-based)				
C-02 GLOBAL – 1	ELEMENT	EVENT		L
ACCIDENTAL EVENT	C-02 GLOBAL - 1	EVENT		L
C-02 GLOBAL – 2	C-03 GLOBAL FAT - 2	ELEMENT	EVENT	H
ACCIDENTAL EVENT	C-02 GLOBAL - 2	C-03 GLOBAL FAT - 2	EVENT	H
C-02 GLOBAL – 2	C-03 GLOBAL EV. - 2	ELEMENT	EVENT	H
ACCIDENTAL EVENT	C-02 GLOBAL - 2	C-03 GLOBAL EV. - 2	EVENT	H

Table 17
Risk ranking of the minimal cutsets grouping for the numerical-based application, reaching a total risk value for every event into analysis

	Treatment – numerical-based RCIs				
	Natural gas	Oil			
	NG-5	O-3	O-4	O-5	O-6
H	0.46	0.47	0.46	0.32	0.46
L	0.71	0.76	0.73	0.40	0.72
	Total				
	1.16	**1.23**	1.20	0.72	1.18

Table 18
Levels of risk in treatment, dependent on the considered cases into analysis

Average values of risk in treatment		
	NG	O
Verbal-based application	I	II
Numerical-based application	I	II

dominant event is O-3. This is expected since the two approaches are based on different scales.

The ranking level, in this case only I and II, which classifies the chains according to the decreasing level of risk is shown in Table 18. This classification is obviously dependent on the events under analysis, on their number, and their characteristics.

4.2.3. Regional transportation

The fault trees and their assumptions in the regional transportation stage applications are the same as the extraction case.

The simulation is carried on per single event, considering the values of Tables 7 and 8.

Three groups of possible cutsets are identified for verbal-based application (H, M, and L, see Table 19), and two (H and L, see Table 21) for numerical-based application, in both cases following the same criteria of definition. Again, the combinations of RCIs (minimal cutsets) with the highest rate of relative importance are those including the indicator C-03 (population immediately affected), counting only fatalities in the verbal-based applications, including injured and evacuees in the numerical-based applications.

For each group of minimal cutsets a risk value is calculated in correspondence to every single considered case. Combining the values of the three groups, the total risk value for each case is calculated (see Tables 20 and 22).

The relative ranking of the events shows the risk dominance of the two oil cases in both verbal-based and numerical-based applications.

The ranking level, in this case only I and II, which classifies the chains according the decreasing level of risk is shown in Table 23. This classification is obviously dependent on the events into analysis, on their number, and their characteristics.

Table 20
Risk ranking of the minimal cutsets grouping for the verbal-based application, reaching a total risk value for every event into analysis

	Regional transportation – verbal-based RCIs				
	Natural gas			Oil	
	NG-6	NG-7	NG-8	O-7	O-8
H	0.03	0.03	0.02	0.04	0.04
M	0.03	0.03	0.03	0.03	0.03
L	0.14	0.13	0.10	0.17	0.17
	Total				
	0.21	0.19	0.15	**0.24**	**0.24**

Table 21
Ranking of the importance of the minimal cutsets for the numerical-based application, based on the importance of the involved basic events (indicators)

Combinations/grouping of indicators and respective relative ranking (regional transportation – numerical-based)				
C-02 GLOBAL - 1	ELEMENT	EVENT		L
ACCIDENTAL EVENT	C-02 GLOBAL - 1	EVENT		L
C-02 GLOBAL - 2	C-03 GLOBAL FAT - 2	ELEMENT	EVENT	H
ACCIDENTAL EVENT	C-02 GLOBAL - 2	C-03 GLOBAL FAT - 2	EVENT	H
C-02 GLOBAL - 2	C-03 GLOBAL INJ - 2	ELEMENT	EVENT	H
ACCIDENTAL EVENT	C-02 GLOBAL - 2	C-03 GLOBAL INJ – 2	EVENT	H
ACCIDENTAL EVENT	C-02 GLOBAL - 2	C-03 GLOBAL EV. – 2	EVENT	H
C-02 GLOBAL - 2	C-03 GLOBAL EV. - 2	ELEMENT	EVENT	H

Table 19
Ranking of the importance of the minimal cutsets for the verbal-based application, based on the importance of the involved basic events (indicators)

Combinations/grouping of indicators and respective relative ranking (regional transportation – verbal-based)					
C-02 GLOBAL - 1	ELEMENT	EVENT	SPATIAL EXTENT		L
ACCIDENTAL EVENT	C-02 GLOBAL - 1	EVENT	SPATIAL EXTENT		L
C-02 GLOBAL - 2	C-03 GLOBAL FAT - 2	ELEMENT	EVENT	SPATIAL EXTENT	H
ACCIDENTAL EVENT	C-02 GLOBAL - 2	C-03 GLOBAL FAT - 2	EVENT	SPATIAL EXTENT	H
C-02 GLOBAL - 2	C-03 GLOBAL INJ - 2	ELEMENT	EVENT	SPATIAL EXTENT	M
ACCIDENTAL EVENT	C-02 GLOBAL - 2	C-03 GLOBAL INJ - 2	EVENT	SPATIAL EXTENT	M
ACCIDENTAL EVENT	C-02 GLOBAL - 2	C-03 GLOBAL EV. - 2	EVENT	SPATIAL EXTENT	M
C-02 GLOBAL - 2	C-03 GLOBAL EV. - 2	ELEMENT	EVENT	SPATIAL EXTENT	M

Table 22
Risk ranking of the minimal cutsets grouping for the numerical-based application, reaching a total risk value for every event into analysis

	Regional transportation – numerical-based RCIs				
	Natural gas			Oil	
	NG-6	NG-7	NG-8	O-7	O-8
H	0.40	0.39	0.39	0.43	0.42
L	0.54	0.53	0.52	0.61	0.61
	Total				
	0.94	0.92	0.91	**1.04**	1.03

Table 23
Levels of risk in regional transportation, dependent on the considered cases into analysis

Average values of risk in treatment		
	NG	O
Verbal-based application	II	I
Numerical-based application	II	I

5. Discussion of single results

The results obtained with the application of the available accidental cases for extraction, treatment, and regional transportation for the coal, natural gas, and oil fuel cycles respects in general the trend of the relative risk ranking for the selected chains. Nevertheless, specific assumptions due to the limited number of cases, their characteristics, and their selection criteria are necessary.

It is very important to state that the values of risk ranking for every single event do not refer to a maximum absolute value. They make sense only when compared among themselves.

Extraction is the only stage where a cross comparison among the three chains is possible. The level of risk of coal and oil can be considered similar, even if the result for the numerical-based cases shows the dominance of coal as it should be the case for this specific step in the fuel cycle. Anyhow, the risk associated to coal and oil for both verbal-based and numerical-based applications in extraction is higher than the risk associated to natural gas. The same observation is also valid when looking to the relative ranking of the single events involved.

The comparison between natural gas and oil is carried on along all the three steps under observation. Considering the verbal-based application of the RCIs, oil is more risky than natural gas in extraction and regional transportation, while the reverse situation is shown in the treatment step. For the numerical-based application, the same trend is confirmed.

These evaluations must be considered in light of this specific case study, where judgment is based on only a limited number of accidental events. From this point of view, the most difficult situation presents itself for the treatment step, where the judgment for natural gas is based only on one available accident, in comparison with the four available for oil.

Nevertheless, the results are very close to those found in the existing literature concerning fossil fuels, see for example (Burgherr and Hirschberg, 2008), and the overall ranking in the next section is going to further confirm the trend.

When looking into the results for each single event, independently from the step of the chain to which it belongs, a question could arise if considering that in some cases relative ranking higher that 1 are obtained, even if dealing with a probabilistic context.

This is a problem that could appear when summing high probabilities for every single cutest. The application of Risk Spectrum in the way proposed is different from normal use and is proven to be efficient to combine scenarios and relatively rank the events according to their importance, but does not have to be seen as a standard application to reach unavailability values.

The definition of the unavailability of the top event (ranking value of every accidental event considered) is calculated according to:

$$Q_{TOP} = \sum_i Q_{MCS,i}, \tag{5.1}$$

where unavailability of the top event Q_{TOP} is the sum of the unavailability of the single cutsets. This normal first order approximation is called *rare event approximation*, which works very well when the probabilities have very low values. This statement shows the origin of the problem in some of our cases, where the total values are sometime higher than 1. We actually work with high probability values.

The previous formula is approximately equivalent to

$$\sum_i Q_{MCS,i} \approx 1 - \prod_i (1 - Q_{MCS,i}). \tag{5.2}$$

The second part, also calculated by Risk Spectrum, is always a first order approximation, but offering better approximation. This part is often called *min cut upper bound*.

This second part is used by the program applying the formula through a step by step process. The process terminates when exceeding 1, or even close enough to 1. In this way, some minimal cutsets from the list are absorbed by the program, and do not appear in the final result.

This can cause discrepancies with the top event unavailability calculated by Risk Spectrum for every single simulation case, where the absorption of some cutsets appears. In the results reported in this paper, all the minimal cutsets available are considered in the sum.

The aim of the methodology proposed in this work is to reach a relative rank of the events. And this is achieved by the proposed method.

Possible issues can appear because we are using high probability values in the basic events when simulating with Risk Spectrum. This is a limitation of the use of PSA-based methodology in such a context. But the ranking is given, and the ranking values must be evaluated in relative comparison among themselves, just to state the importance of the events from the risk point of view.

Passing then to the average values (ranked in Tables 13, 18 and 23), the situation is different. At this level the contact with probability is lost. These are just numbers, and treated like numbers. In any case, values, as before, always make sense only in a relative view, and are not related to any pre-determined maximum value.

6. Overall evaluation

Summing all the average values of relative ranking of each step in every chain, it is possible to obtain overall average values for comparison among fuel cycles. The results here are converted into ranking levels for easier understanding. Table 24 shows the levels according to the results obtained for natural gas and oil cases, adding the average values for extraction, treatment and regional transportation, respectively for verbal-based and numerical-based

Table 24
Levels of risk in total (extraction + treatment + regional transportation) dependent on the considered cases into analysis

Average values of risk in extraction + treatment + regional transportation		
	NG	O
Verbal-based application	II	I
Numerical-based application	II	I

applications; from this evaluation oil results as level I, thus more risky than natural gas. Coal is excluded as involved only in the extraction comparison, while corresponding cases for treatment and regional transportation are not available.

This evaluation is based on the limited amount of available cases, and shows that the rate of risk is higher in oil than in natural gas, for both verbal and numerical based applications. This confirms the general trend in risk evaluation for the oil and natural gas chains, even if limited at the consideration of only three stages along the fuel cycle, and a limited number of accidental events.

This trend for risk concerning oil and natural gas is also confirmed by (Burgherr and Hirschberg, 2008), both for number of fatalities and for number of accidental events.

7. Alternative evaluation paths

The proposed method for comparing the risks of energy systems can be under judgment for a particular issue: the chain-specific energy production.

Actually the proposed method offers a risk ranking based on maximum possible outcomes, thus in comparison with the worst scenarios.

In this section, other two evaluation paths are proposed, taking into consideration the electricity production by chain and applying the same ENSAD selected accidental events. The results are again expressed in relative ranking among the events into analysis.

The values of electricity production by fuels are taken from IEA (IEA, 2007) and are referred to 2005 world statistics. The year 2005 is thus chosen as reference year for this study. The shares of fossil fuels electricity production to the total of 18,235 TW are:

- *Coal*: 40.3%, corresponding to 7351 TW.
- *Natural gas:* 19.7%, corresponding to 3597 TW.
- *Oil*: 6.6%, corresponding to 1201 TW.

For the purpose of the paper, the energy values are converted into MW.

7.1. Introduction of energy weighting factors

The first proposed alternative approach does not substantially change the main process previously introduced (Fig. 2). It includes only an additional step located along the application as shown in Fig. 9.

The weighting factors are calculated as the ratio between the amount of electricity production from a specific chain and the total world electricity generation. Considering the world electricity statistics from (IEA, 2007), their values for the fossil chains under investigation are:

- Coal: 0.403.
- Natural gas: 0.197.
- Oil: 0.066.

These weights are not considered alone, but possible combinations among them are investigated. The final conclusion leads to relate them to the highest weight among those involved in the calculation, in this case that from coal. Terms w_j/w_{MAX} are defined, with value 1 only for coal.

Afterwards, each indicator in normalized value in output from step 4 (Fig. 9) is divided by w_j/w_{MAX}, obtaining:

$$I^*_{ij} = \frac{I_{ij}}{\frac{w_j}{w_{MAX}}} = I_{ij} \cdot \frac{w_{MAX}}{w_j}, \qquad (7.1.1)$$

where i = criterion, and j = event, following the reference codes as in the matrix 3.1.

In fact, this means that the final relative risk ranking of every event is scaled to the maximum electricity production. This approach is chosen to maintain the comparability among events belonging to different chains, as comparison means also the need of uniform evaluation supports.

The output values from step 5 follow the remaining process shown in Fig. 9 to the final relative ranking of the events. The results of the case study, which uses the same data introduced in Section 4, are shown in the following Sections 7.1.1 and 7.1.2, respectively, for verbal-based and numerical-based approaches.

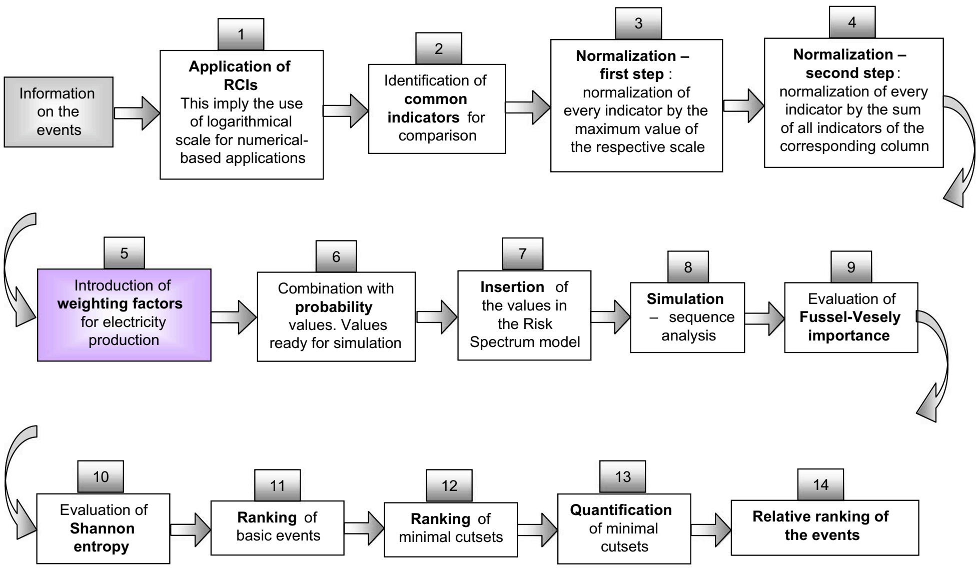


Fig. 9. Introduction of energy weighting factors in the process to evaluate the relative risk ranking of the accidental events for energy systems.

Table 25
Risk ranking of the minimal cutsets grouping for the verbal-based application in extraction including energy weight, reaching a total risk value for every event into analysis

	Extraction – verbal-based RCIs											
	Coal						Natural gas				Oil	
	C-1	C-2	C-3	C-4	C-5	C-6	NG-1	NG-2	NG-3	NG-4	O-1	O-2
M	0.00004	0.00004	0.00004	0.00004	0.00004	0.00004	0.00027	0.00021	0.00015	0.00015	0.01112	0.00995
L	0.00155	0.00135	0.00135	0.00144	0.00144	0.00144	0.0055	0.00474	0.00446	0.00446	0.0627	0.05792
	Total											
	0.0016	0.0014	0.0014	0.0015	0.0015	0.0015	0.0058	0.0049	0.0046	0.0046	0.0738	0.0679

Table 26
Risk ranking of the minimal cutsets grouping for the verbal-based application in treatment including energy weight, reaching a total risk value for every event into analysis

	Treatment – Verbal-based RCIs				
	Natural gas	Oil			
	NG-5	O-3	O-4	O-5	O-6
H	0.0003	0.0077	0.0082	0.0055	0.0082
M	0.0003	0.0077	0.0082	0.0055	0.0082
L	0.0075	0.0555	0.0671	0.0298	0.0671
	Total				
	0.008	0.071	0.084	0.041	0.084

Table 27
Risk ranking of the minimal cutsets grouping for the verbal-based application in regional transportation including energy weight, reaching a total risk value for every event into analysis

	Regional transportation – verbal-based RCIs				
	Natural gas			Oil	
	NG-6	NG-7	NG-8	O-7	O-8
H	0.0005	0.0004	0.0004	0.0126	0.0126
M	0.0001	0.0001	0.0000	0.0032	0.0032
L	0.0059	0.0052	0.0041	0.0621	0.0621
	Total				
	0.007	0.006	0.005	0.078	0.078

7.1.1. Verbal-based applications of the RCIs

See Tables 25–27.

7.1.2. Numerical-based applications of the RCIs

See Tables 28–30.

7.1.3. Overall evaluation

The final results for the approach using weighting factors are shown in Table 31 for extraction (the only step including coal) and in Table 32 for natural gas and oil across the three available steps. The chains classification is divided into levels (I, II, and III) according to the decreasing level of risk.

Table 32 recalls the results obtained with the main method and shown in Table 24, where oil has a higher risk impact than natural gas, as confirmed also by statistics. The real effects of this modified methodology are clear when looking at Table 31, which shows the

Table 29
Risk ranking of the minimal cutsets grouping for the numerical-based application in *treatment* including energy weight, reaching a total risk value for every event into analysis

	Treatment – numerical-based RCIs				
	Natural gas	Oil			
	NG-5	O-3	O-4	O-5	O-6
H	0.01	0.11	0.10	0.03	0.10
M	0.01	0.07	0.07	0.09	0.07
L	0.14	0.46	0.45	0.24	0.44
	Total				
	0.16	0.64	0.62	0.36	0.61

Table 30
Risk ranking of the minimal cutsets grouping for the numerical-based application in *regional transportation* including energy weight, reaching a total risk value for every event into analysis

	Regional transportation – numerical-based RCIs				
	Natural gas			Oil	
	NG-6	NG-7	NG-8	O-7	O-8
M	0.02	0.02	0.02	0.16	0.16
L	0.11	0.11	0.11	0.37	0.37
	Total				
	0.13	0.12	0.12	0.53	0.53

Table 31
Levels of risk in extraction, dependent on the considered cases into analysis

Average values of risk in extraction			
	Coal	Natural gas	Oil
Verbal-based application	III	II	I
Numerical-based application	III	II	I

Table 32
Levels of risk in total (extraction + treatment + regional transportation) dependent on the considered cases into analysis

Average values of risk in extraction + treatment + regional transportation		
	NG	O
Verbal-based application	II	I
Numerical-based application	II	I

Table 28
Risk ranking of the minimal cutsets grouping for the numerical-based application in *extraction* including energy weight, reaching a total risk value for every event into analysis

	Extraction – numerical-based RCIs											
	Coal						Natural gas				Oil	
	C-1	C-2	C-3	C-4	C-5	C-6	NG-1	NG-2	NG-3	NG-4	O-1	O-2
L	0.08	0.07	0.07	0.07	0.07	0.07	0.13	0.12	0.12	0.12	0.59	0.55

Table 33
Risk ranking of the minimal cutsets grouping for the numerical-based application in *extraction* including evaluation in respect of the chain-specific electricity production, reaching a total risk value for every event into analysis

	Extraction											
	Coal						Natural gas				Oil	
	C-1	C-2	C-3	C-4	C-5	C-6	NG-1	NG-2	NG-3	NG-4	O-1	O-2
H	0.26	0.24	0.23	0.22	0.21	0.21	0.15	0.14	0.13	0.13	0.24	0.21
M	0.20	0.21	0.22	0.22	0.23	0.23	0.25	0.25	0.25	0.25	0.21	0.23
L	0.71	0.70	0.68	0.67	0.66	0.66	0.54	0.53	0.50	0.51	0.69	0.65
	Total											
	1.17	1.15	1.13	1.11	1.10	1.10	0.94	0.92	0.88	0.89	1.15	10.8

Table 34
Risk ranking of the minimal cutsets grouping for the numerical-based application in *treatment* including evaluation in respect of the chain-specific electricity production, reaching a total risk value for every event into analysis

	Treatment				
	Natural gas			Oil	
	NG-5	O-3	O-4	O-5	O-6
H	0.46	0.47	0.46	0.32	0.46
L	0.72	0.75	0.73	0.41	0.72
	Total				
	1.18	**1.22**	1.20	0.73	1.18

Table 35
Risk ranking of the minimal cutsets grouping for the numerical-based application in *regional transportation* including evaluation in respect of the chain-specific electricity production, reaching a total risk value for every event into analysis

	Regional transportation				
	Natural gas			Oil	
	NG-6	NG-7	NG-8	O-7	O-8
H	0.39	0.39	0.39	0.43	0.42
L	0.54	0.54	0.53	0.62	0.61
	Total				
	0.94	0.94	0.91	**1.05**	1.03

lowest level of risk for coal, which in extraction is contrary to statistics.

It must be stated that the relative risk value for natural gas and oil must be read ‘as if’ they produce the same amount of electricity as coal. Thus, the conclusion should be that at the same level of useful energy production, coal is less risky than natural gas, and far less risky than oil.

This conclusion is in any case misleading, first because it considers only few events, and second because enlarging risk to a larger scale with such an approach does not take into consideration possible improvements in a specific technology when it is dealing with a higher electricity production.

Therefore, the present approach is not suggested as convenient, based on the limitations of our judgment.

7.2. Introduction of RCIs scales based on electricity generation per fuel and normalization according to MWh of electricity produced

This second alternative approach change the main process more radically, modifying the scales of the RCIs and eliminating the verbal-based approach, even if the description of the process follows the same steps as shown in Fig. 2.

The numerical values extracted from the source of information are normalized according to the chain specific electricity production expressed in MW.

It is supposed that the indicators C-04, C-05, C-06, C-07, and C-08 (see Table 1), which initially had only verbal-based evaluation methods, are modified to numerical values to fit the method.

Step number three as from Fig. 2 is processed considering as maximum value the total world electricity production.

The grouping and ranking procedure proceed according to the first main approach and the results are shown in the following Sections 7.2.1 and 7.2.2.

7.2.1. Numerical-based applications of the RCIs

See Tables 33–35.

Table 36
Levels of risk in extraction, dependent on the considered cases into analysis

Average values of risk in extraction			
	Coal	Natural gas	Oil
Numerical-based application	I	III	II

Table 37
Levels of risk in total (extraction + treatment + regional transportation) dependent on the considered cases into analysis

Average values of risk in extraction + treatment + regional transportation		
	NG	O
Numerical-based application	II	I

7.2.2. Overall evaluation

The final chain ranking shown in Tables 36 and 37 confirms exactly the conclusions reached with the main method based on the maximum impact of the events (also in respect of the numerical values behind the levels categories I, II, and III, which arrange risks from the highest (I) to the lowest (III) level).

The reason resides in the methodology itself, as in both cases a normalization process is followed, and additionally on the fact that the electricity productions from coal, natural gas, and oil have the same order of magnitude.

The approach can be considered equivalent to the main one initially presented in this paper, with the only exception that it does not allow the verbal-based evaluation.

8. Conclusion

The paper presented and discussed a comparative methodology to rank and compare energy-related risks. The method, based on a set of RCIs, has its core and innovative aspects in the grouping and ranking procedure, which relies on a PRA-based logic-related process to obtain the final results.

The theoretical development is validated by the application to a set of accidental events affecting three chosen chains of fossil fuels.

The accidents analysed are extracted from the ENSAD database, with the support of PSI.

The overall average level of risk for natural gas and oil, calculated across three steps of the fuel cycle, confirmed the usual trend of risk for the two chains.

Two other alternative evaluation paths including the chain-specific electricity production are introduced and discussed, confirming the validity of the main method presented.

The practical application of the grouping and ranking methodology showed some limitations linked to the use of the simulation program; the program is designed for PRA applications and thus to deal with low probabilities, while here the assumed probabilities have high values.

These limitations are not at all affecting both the method and the outcomes, but only mean that the results must be read in relative way and do not have absolute meaning.

The overall methodology cannot be considered complete at this stage, but need a further uncertainty investigation, which is currently under development.

Acknowledgements

Particular thanks are due to Peter Burgherr (Paul Scherrer Institut, CH) for the important contribution given to the development of this work.

References

Burgherr, P., Hirschberg, S., 2008. Severe accident risks in fossil energy chains: a comparative analysis. Energy 33 (4), 538–553 <http://dx.doi.org/10.1016/j.energy.2007.10.015>.

Burgherr, P., Hirschberg, S., Hunt, A., Ortiz, R.A., 2004. Severe accidents in the energy sector, Final Report to the European Commission of the EU 5th Framework Programme, New Elements for the Assessment of External Costs from Energy Technologies (NewExt), DG Research, Technological Development and Demonstration (RTD), Brussels, Belgium.

Colli, A., Vetere Arellano, A.L., Kirchsteiger, C., Ale, B.J.M., 2008. Risk characterisation indicators for risk comparison in the energy sector. Safety Science <http://dx.doi.org/10.1016/j.ssci.2008.01.005>.

Colli, A., Vetere Arellano, A.L., Kirchsteiger, C., 2005. Development of a General Scheme for Fuel Cycles and Life Cycles from all Energy Technologies as a Basis for the European Energy Risk Monitor (ERMON), EUR 21735 EN, Publication of the European Commission Joint Research Centre, Petten, The Netherlands.

Haimes, Y.Y., 2004. Risk Modeling, Assessment, and Management, second ed. John Wiley & Sons Inc.. ISBN 0-471-48048-7.

Hirschberg, S., Burgherr, P., Spiekerman, G., Dones, R., 2004. Severe accidents in the energy sector: comparative perspective. J. Hazard. Mater. 111, 57–65.

Hirschberg, S., Spiekerman, G., Dones, R., 1998. Severe accidents in the energy sector – first ed., PSI Report No. 98-16, Paul Scherrer Institut, Villigen PSI, Switzerland, 1998.

Hohenemser, C., Kates, R.W., Slovic, P., 2000. The nature of technological hazards", chapter 10 from the book: the perception of risk. In: Slovic, P. (Ed.), Risk, Society and Policy. Earthscan.

Hohenemser, C., Kasperson, R.E., Kates, R.W., 1985. Causal Structure in Perilous Progress: Managing the Hazards of Technology. Westview Press, Boulder, CO.

International Energy Agency, "Key World Energy Statistics", 2007. <http://www.iea.org/Textbase/nppdf/free/2007/key_stats_2007.pdf>.

Jaynes, E.T., 2003. In: Larry Bretthorst, G. (Ed.), Probability Theory: The Logic of Science, ISBN-13: 9780521592710, ISBN-10: 0521592712. doi: 10.2277/0521592712.

Kasperson, J.X., Kasperson, R.E. (Eds.), 2001. Global Environmental Risk. United Nations University Press.

RiskSpectrum® PSA Professional is developed and maintained by Relcon Scandpower AB in Sweden. <http://www.riskspectrum.com/>.

Serbanescu, D., 1991. A new approach to decision making in different phases of PSA studies. In: Proceedings of the International Symposium Use of Probabilistic Safety Assessment for Operational Safety PSA '91, IAEA –NEA–OECD, Vienna, 1991.

Shannon, C.E., 1948. A mathematical theory of communication. The Bell System Technical Journal 27. pp. 379–423, 623–656.

Safety, Reliability and Risk Analysis: Theory, Methods and Applications – Martorell et al. (eds)
© 2009 Taylor & Francis Group, London, ISBN 978-0-415-48513-5

PRA-type study adapted to the multi-crystalline silicon photovoltaic cells manufacture process

A. Colli & D. Serbanescu
EC DG Joint Research Centre, Institute for Energy, Petten, The Netherlands

B.J.M. Ale
TU Delft, Policy and Management, Delft, The Netherlands

ABSTRACT: The paper presents a Probabilistic Risk Assessment type (PRA-type) study developed by the Institute of Energy of the Joint Research Centre of the European Commission (JRC-IE) for non-nuclear energy applications and adapted to the manufacture process for multi-crystalline silicon solar cells production. The study is in the context of a project, which is part of a PhD study that aims to develop a methodology to compare risks across different energy systems. Risk assessment and risk data collection efforts are under way in most energy sectors (nuclear, fossil, hydropower), making possible comparisons easier. The photovoltaic (PV) sector, as a new rapidly growing energy technology, offers opportunities for assessing possible risks mainly based on the quantity of dangerous chemicals used, but there seems to be a lack of reported information on its risk events. This situation makes it difficult to analyze the impact of the PV technology, especially if the attention is on human health. Therefore, other well-known methods to assess the safety level of PV manufacturing facilities, such as PRA, can be used to assess corresponding risk levels. The PRA methodology allows to evaluate preliminary quantification figures for failure frequencies, and to demonstrate the possible advantages in identifying the failure scenarios of the process itself, so that countermeasures can be considered. This paper presents first a detailed analysis of the PV manufacture process, conducted at a methodological level (knowledge of the single processes at every step, with chemicals introduced, and resulting as reaction products) as well as at a technical level (machinery involved, auxiliary systems). Next, on this basis, an event tree and fault tree model are constructed and the corresponding analysis performed, using data available from generic chemical industry data-bases. The results of this analysis show that it is possible to quantify the frequency of failures of such processes leading to health challenges and also to identify the scenarios leading to those end states. Even if the figures resulting from the existing models based on the information available so far indicate that such probabilities are unlikely in comparison with other industries, nevertheless the results indicate the existence of weak links. Such weak points could lead to possible health threats. The benefits of using such approaches in conjunction with other design tools are clear when performing risk reviews before events happen. Such an application would be in line with the best practice on these issues from other industrial fields (aviation, aero-space, nuclear, some other chemical processes). The use of such models in the framework of risk comparison could complement the data collected to support the development of the knowledge database on risks for various energy sources.

1 INTRODUCTION

Although the world's PV industry is still new when compared to other traditional energy sectors, PV is already now considered to be among the major renewable energy technologies of the future, with a positive growth rate for the coming years, and offering the benefits of an increasing number of jobs in Europe. The growth of PV is expected to be boosted also by the decision of the Council of the European Union in March 2007; "a binding target of a 20% share of renewable energies in overall EU energy consumption by 2020" (Council of the European Union 2007) has been agreed, which will also affect PV through the implementation of national programs.

However, in parallel to the high growth rate in the PV sector, there is a real need to increase attention also to the possible proportionate rise in risks. Risk considerations are necessary for both existing and for new technologies, and the PV sector shall thus not be excluded.

PV electricity generation is a zero-emission process regardless of which technology (materials and manufacturing process) is used, but the production processes of solar modules involve chemical sub-stances, which, like in any other industrial process, can pose a threat to occupational safety, in terms of acute or chronic hazards, as well as to the environment, if they are not properly handled. Possible risks from dangerous substances can come mainly from release of chemicals, toxic fumes inhalation, fire and explosion.

The amount of substances used in PV manufacture is extremely low compared to the chemical process industry, as shown by the Energy research Centre of the Netherlands (ECN) in their overview of the amounts of substances used for crystalline silicon module production (ECN 2007). However, the above-described rapid current growth of the PV sector and its related production needs could lead to the use of much larger amounts of dangerous chemical substances and it must be ensured that this does not put significant additional risk to human health and the environment.

The hazards associated with the manufacture process of the photovoltaic cells have been largely discussed (see for example (Fthenakis 2003a)). On the other side, there are no information and reported incidental events easily accessible from the interested industrial sector and the semiconductor industry is thus, generally taken as a bench-mark.

The lack of available safety data and information concerning the photovoltaic manufacture industry, has led to evaluate the probability of some particular events using a PRA-based approach. In (Fthenakis 2003b) the fault tree analysis for the photovoltaic cell manufacture process is presented as a method for accident prevention available to the industry.

A fault tree is a modelling tool used in the qualitative and quantitative analysis of a system to develop a deterministic description of the occurrence of a selected top event, based on the occurrence or non-occurrence of the intermediate and basic events in a logic sequence. Using such a Boolean model and appropriate modelling data, the probability of occurrence of the fault tree's top event can be determined together with failure sequences leading to that undesired top event.

Basis of a fault tree analysis is a proper definition of the system of interest and the top event to be investigated. Tracing backwards in the causal sequence, failures that could lead to the top event can be identified, until failures are reached that cannot be reduced any more or cannot be quantified. Further-more, boundaries of the system have to be assumed, taking into account external, internal and temporal aspects.

2 OVERVIEW OF CHEMICAL SUBSTANCES IN THE PROCESS AND THEIR ASSOCIATED RISKS

Along the investigation of the specific process into analysis for the fault tree study, it is important to have knowledge of the different chemical sub-stances entering, and being released as vapours or re-action products from the process itself.

An overview and characterization of all the hazardous substances, respectively entering and re-leased from the process, is shown in Table 1 and Table 2. The substances are investigated concerning their indication of danger and their classification according to

Table 1. Chemical substances introduced in the multi-crystalline photovoltaic cell manufacture process into analysis.

Substance	Indication of danger according to Directive 67/548/EEC (updated version Directive 92/32/EEC)	Associated risk
Nitric acid (HNO_3)	O: Oxidizing C: Corrosive	Skin irritation, severe burns.
Hydrogen fluoride (HF)	T+: Very toxic C: Corrosive	Toxicity, severe burns.
Potassium hydroxide (KOH)	C: Corrosive	Severe burns.
Hydrogen chloride (HCl)	T: Toxic C: Corrosive	Toxicity, severe burns.
Oxygen (O_2)	O: Oxidizing	Contactwith combustible material may cause fire.
Nitrogen (N_2)	Not classified	Oxygen consumption in air
Phosphoryl chloride ($POCl_3$)	T+: Very toxic C: Corrosive	Toxicity, severe burns, reacts violently with water.
Carbon tetrafluoride (CF_4)	Not classified	Global warming potential.
Silicon hydride (silane) (SiH_4)	Not classified	Fire/explosion.
Ammonia (NH_3)	T: Toxic N: Dangerous for the environment	Fire, toxicity, severe burns.
Silver (Ag)	Not classified	In metallisation paste.
Aluminuim (Al)	F: Highly flammable (if powder)	In metallisation paste.
Solvents:		
Isomethyl butyl ketone ($C_6H_{12}O$)	F: Highly flammable Xn : Harmful	Fire, harm, irritation.
Terpineol ($C_{10}H_{18}O$)	Not classified	Fire, harm, irritation.

Table 2. Output chemical substances from the multicrystalline photovoltaic cell manufacture process into analysis. The information for hydrogen fluoride, nitrogen, ammonia, nitric acid, and solvents is considered in Table 1 and not repeated.

Substance	Indication of danger according to Directive 67/548/EEC (updated version Directive 92/32/EEC)	Associated risk
Sodium hydroxide (NaOH)	C: Corrosive	Severe burns.
Nitrogen dioxide NO_X (NO2)	T+: Very toxic	Toxicity.
Chlorine (Cl_2)	T: Toxic N: Dangerous for the environment	Toxicity, skin burns.
Diphosphorus pentoxide (P_2O_5)	C: Corrosive	Skin irritation, severe burns, harmful if inhaled.
Tetrafluoro silane (SiF_4)	Not classified	Toxicity.
Fluorine (F_2)	T+: Very toxic C: Corrosive	Fire, toxicity, severe burns.
Silicon dioxide (SiO_2)	Not classified	Toxicity.
Fluorosilicic acid (H_2SiF_6)	C: Corrosive	Severe burns.

the European Directive 67/548/EEC (updated version consisting of Directive 92/32/EEC) on the approximation of the laws, regulations and administrative provisions relating to the classification, packaging and labelling of dangerous substances. The associated risks in case of exposure to the substance are also indicated.

It is important to highlight that the amount of dangerous chemical substances involved in the process is very small (ECN 2007) compared to other chemical process industries, thus the possible related risk is also more limited.

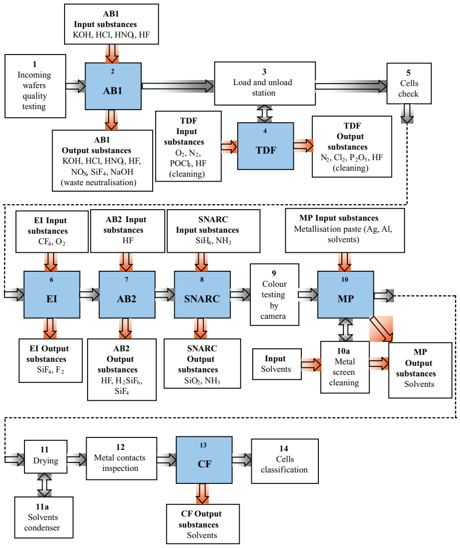


Figure 1. The multicrystalline silicon photovoltaic cells manufacture process. The highlighted boxes are those including the processes which required special modeling due to the chemical substances involved. The codes are: AB = acid bath, TDF = tube diffusion furnace, EI = edge isolation, SNARC = silicon nitride anti-reflective coating, MP = metallization process, CF = contact firing.

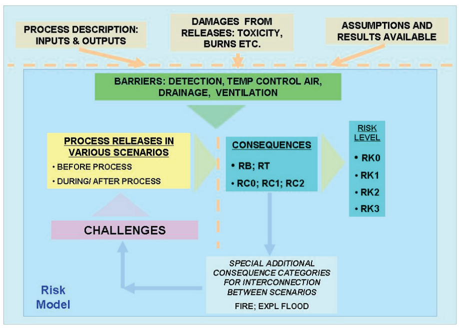


Figure 2. Main Flow of a quantitative risk analysis. For the explanation of consequences and risk categories see Table 3.

3 METHODOLOGY

3.1 *Main features of the model and method used*

The modelling of the process using the risk type approach is based on the standards used by the nuclear industry as shown in (NUREG2300) adapted to the specificity of the photovoltaic manufacturing process.

In order to perform this adaptation a series of assumptions and clarifications are needed. Previous work, showed in (Serbanescu et al. 2008) and (Serbanescu 2006), clarifies how the PRA process can be performed in other areas than the nuclear field and identifies which are the main challenges. However in this paragraph a short list of the main features of the model and the steps of the method are presented.

The target of the PRA modelling for the photovoltaic manufacturing facilities is to support the

Table 3. Definitions of the end states (consequences and risk levels).

Release/ risk category	Description of category	Rank
RB	Release/spill leading to burns.	H
RT	Release/spill being toxic.	H
RC0	Release/spill below imposed targets by regulations.	H
RC1	Release/spill reaching imposed targets by regulations.	M
RC2	Release/spill above imposed targets by regulations.	H
RK0	Very low risk induced by release/spill	H
RK1	Low risk induced by release/spill	M
RK2	Medium risk induced by release/spill.	H
RK3	High risk induced by release/spill.	M
EXPL	Intermediate consequence category coding scenarios which could lead to explosions.	M
FIRE	Intermediate consequence category coding scenarios which could lead to fire.	M
FLOOD	Intermediate consequence category coding scenarios which could lead to flood.	M

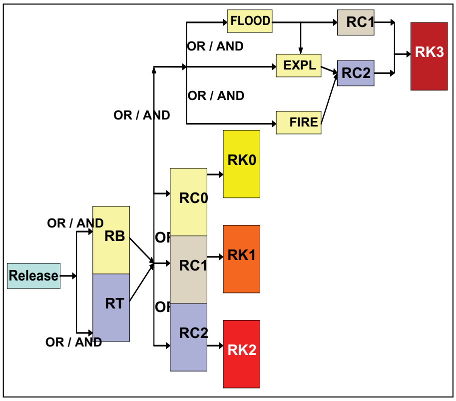


Figure 3. End States for the evaluation of postulated scenarios. For the explanation of release and risk categories see Table 3.

assessment of the corresponding risk levels of the process, the potential weak links and possible future improvements.

An attempt has been made to describe the installation phases, as shown in Figure 1. However, due to the limited information accessible in open source, the

Table 4. List of initiating events (IE).

Code of initiating event	Description
Releases/spills at the input to process	
IE_RELIN_AL_MP	IE spill Al at input into MP.
IE_RELIN_CF4_EI	IE release CF4 at input into edge insulation (EI).
IE_RELIN_HCL_AB1	IE spill HCL at input into acid bath 1.
IE_RELIN_HF_AB1	IE release HF at input into acid bath 1.
IE_RELIN_HF_AB2	IE release HF at input into acid bath 2.
IE_RELIN_HNO3_AB1	IE release HNO3 at input into acid bath 1.
IE_RELIN_KOH_AB1	IE spill KOH at input into acid bath 1.
IE_RELIN_N2_TDF	IE N2 release at input in TDF.
IE_RELIN_NH3_SNARC	IE release NH3 at input into SNARC.
IE_RELIN_O2_EI	IE release O2 at input into EI.
IE_RELIN_O2_TDF	IE O2 release at input in TDF.
IE_RELIN_POCL3_TDF	IE POCL3 release at input TDF.
IE_RELIN_SIH4_SNARC	IE release SIH4 at input into SNARC.
IE_RELIN_SOLVENT_MP	IE spill solvents at input into MP.
Releases/spills at the output to process	
IE_RELOUT_CL2_TDF	IE CL2 release at output TDF.
IE_RELOUT_F2_EI	IE F2 release at output EI.
IE_RELOUT_H2SIF6_AB2	IE H2SIF6 release output at AB2.
IE_RELOUT_HCL_AB1	IE release HCL at output of AB1.
IE_RELOUT_HF_AB1	IE HF release at output AB1.
IE_RELOUT_HF_AB2	IE release at output AB2.
IE_RELOUT_HNO3_AB1	IE release HNO3 at output from AB1.
IE_RELOUT_KOH_AB1	IE spill KOH at output in acid bath 1.
IE_RELOUT_N2_TDF	IE N2 release at output TDF.
IE_RELOUT_NH3_SNARC	IE NH3 release at output SNARC.
IE_RELOUT_NOX_AB1	IE NOX release at output AB1.
IE_RELOUT_P2O5_TDF	IE P2O5 release at output TDF.
IE_RELOUT_SIF4_AB1	IE SIF4 release at output AB1.

(*Continued*)

Table 4. (*Continued.*)

Code of initiating event	Description
IE_RELOUT_SIF4_AB2	IE SIF4 release at output AB2.
IE_RELOUT_SIF4_EI	IE SIF4 release at output EI.
IE_RELOUT_SIO2_SNARC	IE SIO2 release at output AB2.
IE_RELOUT_SOLV_CF	IE solvent release at output CF.
IE_RELOUT_SOLV_DRY	IE solvent release at output Dryer.
IE_RELOUT_SOLVENT_MP	IE Solvent at output MP.
Area events	
IE_SEIS	IE earthquake higher than design level.
IE_EXPL	IE explosion in manufacturing area-external event.
IE_FIRE	IE area event fire in the manufacturing zone.
IE_FLOOD	IE flood in manufacturing area.

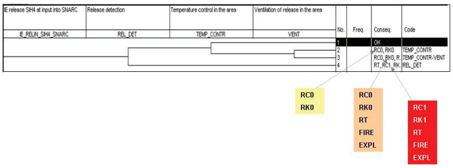


Figure 4. Sample event tree with barriers and end states.

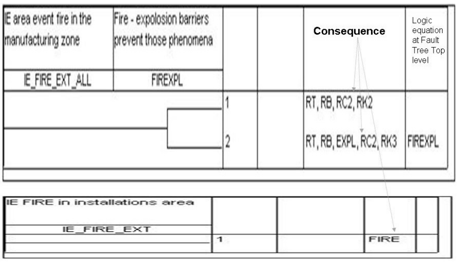


Figure 5. Event tree for fire/explosion scenario.

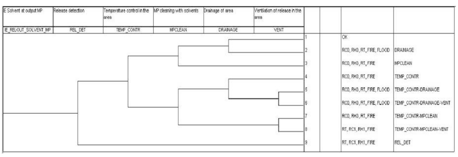


Figure 6. Typical event tree for the releases.

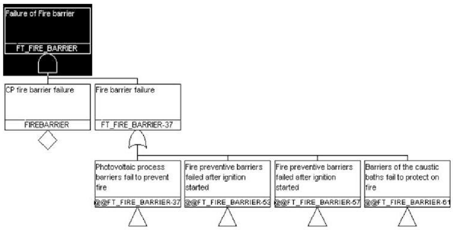


Figure 7. Sample fault tree for a barrier.

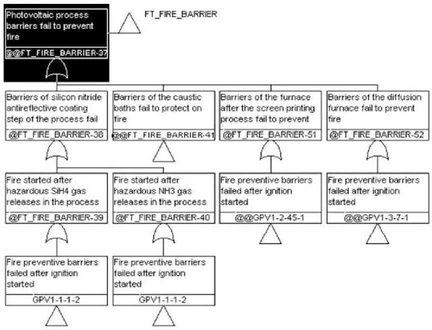


Figure 8. Sample fault tree for a barrier.

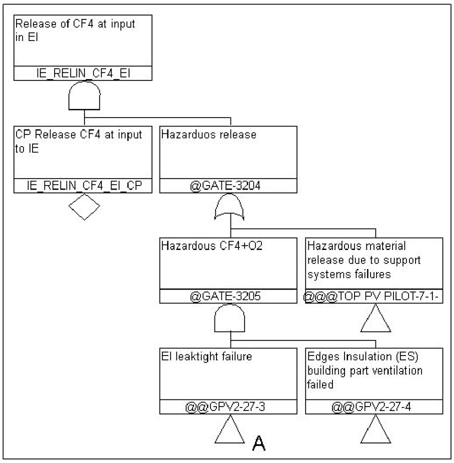


Figure 9. Sample fault tree for a IE frequency calculation. The top event considered covers the release of CF4 at input of the edge isolation (EI) process. Branch A is further developed as shown in the following Figure 10.

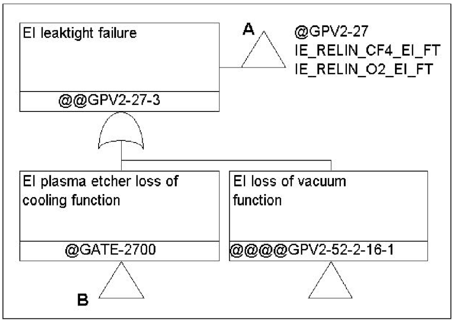


Figure 10. As continuation from previous Figure 9, the further development of branch A is presented. The path along branch B is shown in the following Figure 11.

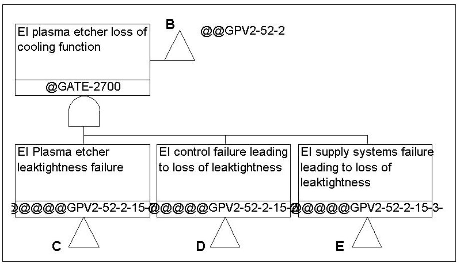


Figure 11. Development of branch B as from Figure 10. Further investigation is needed for gates C, D, and E. The progress is shown in the following Figure 12, 13 and 14.

results obtained will have relevance only from the point of view of highlighting the methodology and identifying relative importance and ranking of various issues between them.

The main flow of the PRA methodology used for this case is shown in Figure 2. The process of developing the PRA model is based on process description and definition of the possible damages of various failures (as described in previous paragraphs).

Based on this information a set of assumptions are made related to the possible scenarios and their results. These assumptions are based on existing information, too. However they could be flagged as initial questionable inputs to the model, for which later on extensive sensitivity analyses are performed to check the impact and importance of each of them to the results so that to seek systematically for further model reviews based on new updated information on those issues.

The next step in building the model is to define the barriers assumed by design to cope with various challenges and dangerous results so that risk to workers

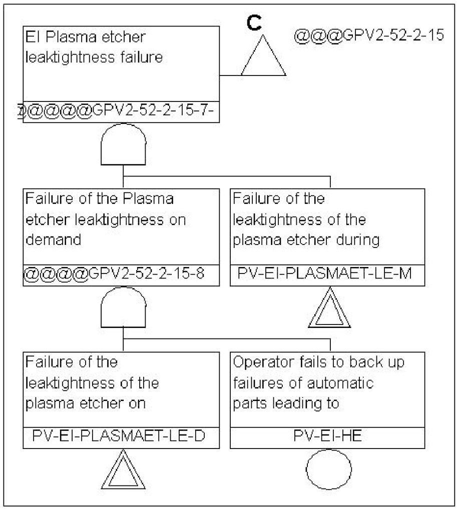


Figure 12. Development of branch C as from Figure 11, reaching the basic events. The events identified with the double triangle could be investigated in more details and could be further developed; anyhow, for the level of this study it has been decided to stop at this stage, mainly for the unavailability of further, more detailed, information.

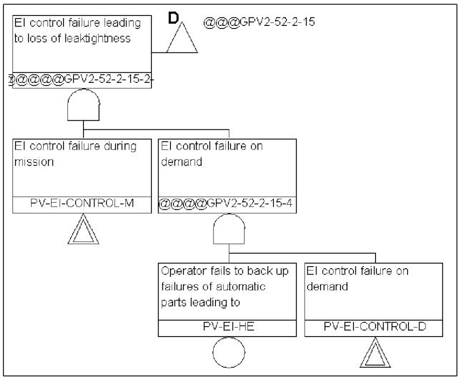


Figure 13. Development of branch D as from Figure 11, reaching the basic events. The events identified with the double triangle could be investigated in more details and could be further developed; anyhow, for the level of this study it has been decided to stop at this stage, mainly for the unavailability of further, more detailed, information.

and public will be as low as possible. After defining the possible challenges that could happen, the barriers to them, and the possible end states in each case, a set of scenarios can be built by using specialized computer

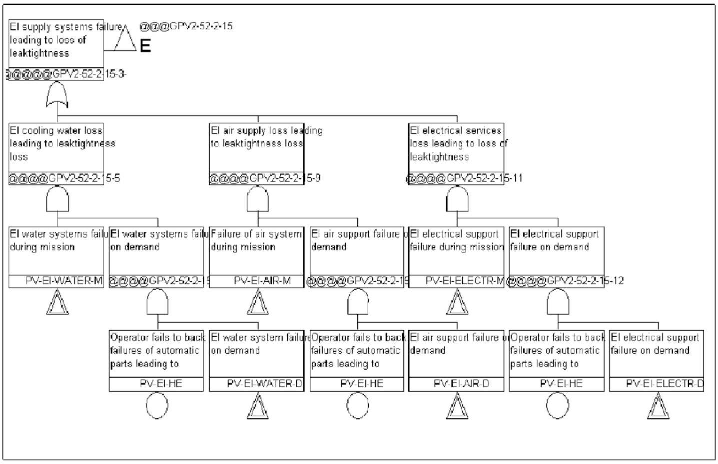


Figure 14. Development of branch E as from Figure 11, reaching the basic events. The events identified with the double triangle could be investigated in more details and could be further developed; anyhow, for the level of this study it has been decided to stop at this stage, mainly for the unavailability of further, more detailed, information.

software (as for instance RiskSpectrum® PSA Professional (© Relcon Scandpower AB 2008)). The results of the case calculations for those scenarios give us the group of all the combinations of the installation components failures leading to a certain consequence. The modelling in RiskSpectrum uses special consequence categories introduced in the event trees, assuring the association between various scenarios. A special connection is created to link consequences and scenarios when they express identical situations (e.g. fire is considered both among scenarios and consequences); this approach is shown by the feedback line in Figure 2.

The definition of the end states (consequences and risk levels) are shown in Table 3, and their postulated combination are illustrated in Figure 3.

The end states definition is used to qualify the termination of each branches of the scenarios build in the so called event trees for all the postulated challenges to the installation as listed in Table 4.

The end states are applied to all the resulting scenarios given that the challenges from Table 4 happen. The list of challenges from Table 4 is called list of Initiating Events (IE). The IE basically belong to three groups: releases before the process, releases during and after the process, and challenges due to so called area events (floods, fires, explosions, earthquakes).

The quantification of the scenarios is based on the end states to which they lead (consequence categories). This quantification allows the evaluation of the risk impact of components and groups of components, which are subsequently ranked correspondingly.

Given the data limitations, the results are mainly significant from the point of view of relative ranking and importance of different elements, rather than from the point of view of absolute values of their risk impact.

3.2 *Some specific modeling issues*

There are some specific issues of the event trees in this particular model, related mainly to data limitations and scarce information on some design features of the assumed barriers. However by considering them as input assumptions and performing sensitivity calculations on their relative impact, the future iterations considering improved data and assumptions could be directed by risk ranking of the main contributors to the final results.

The event trees have the form portrayed in Figures 4, 5, and 6, and they reflect the generic results of representing such type of scenarios as derived in previous papers on analogue cases (Serbanescu et al. 2007).

The event trees consist of a representation of braches indicating success or failure after a given IE happened and various barriers (represented in the upper horizontal bar) fail to protect the installation.

The description of the failure of barriers is performed in a set of trees defining the manner the barrier can fail to perform its function, as represented in Figures 7 and 8.

The frequency of initiating events is calculated in PRA using either results from existing database of failures (if that exists) or by developing special type of

CATEGORY OF CONTRIBUTOR	CONTRIBUTOR	Rank of the impact of a given contributor to the end states								
		RB	RT	RC0	RC1	RC2	RK0	RK1	RK2	RK3
RELEASE AT INPUT OF PROCESS	SILANE	L	L	L	L	M	L	L	L	M
	OTHER FLAMABLE	L	L	L	L	M	L	L	M	M
	OTHER NON FLAMMABLE	M	M	M	M	L	M	M	L	L
RELEASE AT OUPUT OF PROCESS	SILANE	M	M	L	M	H	L	M	M	H
	OTHER FLAMABLE	M	M	L	M	H	L	M	M	H
	OTHER NON FLAMMABLE	L	L	M	M	H	M	M	L	L
AREA EVENTS	SEISMIC	L	L	NA	NA	M	NA	NA	L	L
	FLOOD	VL	VL	VL	VL	L	VL	VL	L	L
	FIRE	L	L	VL	VL	H	VL	VL	M	H
	EXPLOSIONS	L	L	VL	VL	H	VL	VL	M	H
INTERNAL PROCESS DESIGN ELEMENTS	LEAKTIGHNESS & VACUUM	L	L	L	L	M	L	L	M	L
	SUPPORT SYSTEMS	L	L	L	L	M	L	L	M	L
	HUMAN ERRORS	L	L	L	L	M	L	L	M	L
	OTHER	L	L	L	L	L	VL	VL	L	L
BARRIERS AS PROVIDED SO FAR TO PROTECT FROM DAMAGES DUE TO EVENTS / RELEASES	DETECTIOIN OF RELEASE/SPILL	M	M	L	M	M	L	M	M	L
	CLEANING ACTIONS TO PREVENT/LIMIT RELEASE/SPILL	M	M	M	L	M	M	L	M	L
	NEUTRALIZATION AFTER PROCESS TO PREVENT	L	L	L	L	M	L	L	M	L
	VENTILLATION OF RELEASE	L	L	L	L	M	L	L	M	M
	FIRE AND EXPLOSION BARRIERS	NA	NA	NA	NA	H	NA	NA	M	H
	DRAINAGE OF SPIL	M	M	M	L	M	M	L	M	M

Figure 15. Main results of the PRA for photovoltaic manufacturing process.

fault trees for the IE frequency calculation (if there are no data on IE). A sample for such fault trees built in our case is represented in Figures 9, 10, 11, 12, 13 and 14.

4 MAIN RESULTS AND DISCUSSIONS

The results are summarized in Figure 15 and represent the rank of the impact of a given contributor from the model to the risk.

There are two main perspectives important from the point of view of the impact of the results: first is the impact of various releases and IE, and second is related to the role and the ranking of impact to cope with risk challenges for various components and/or barriers assumed by design for the installation.

The coding is presented in qualitative manner and has a relative character (considering the relation between them of the contributors). The impacts are coded with H, M, L, and VL, respectively for high, medium, low, and very low impact.

More details are represented in Figures 16, 17 and 18.

The following main observations can be made based on the results obtained so far:

- There is a high contribution of all the releases after the process (silane, other flammable and non flammable) on the highest release category defined (RC2). This high contribution is accompanied by a high contribution to the risk values for all flammable substances. Highest risk (RK3) is associated with fire and explosions.
- The output release of the flammable substances has a lower impact on risk, but still significant.
- For the release/spill of substances before the process there is lower impact on risk than for the same substances after/during the process. However the risk for flammable is still significant.

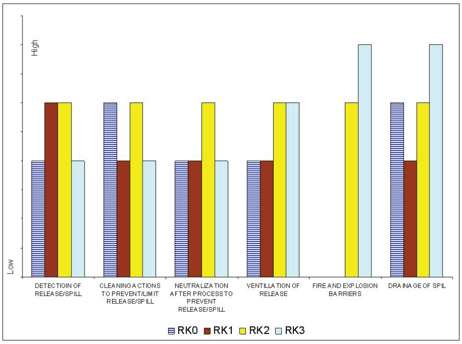


Figure 16. Main results of the PRA study for the specific PV manufacturing process, showing the level of contribution to risk of various barriers and systems. Cleaning actions and drainage of spill have the highest contribution to the low risk category RK0, while the highest input for high risk categories RK2 and RK3 comes from ventilation, fire and explosion, and drainage.

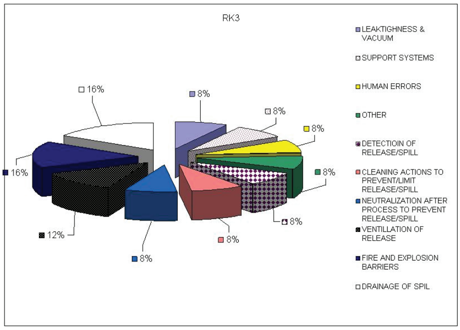


Figure 17. Detailed information concerning the contributors to RK3, as from Figure 16. No really dominant contribution is shown, even if the highest percentage is shared by fire and explosion barriers, and drainage of spill.

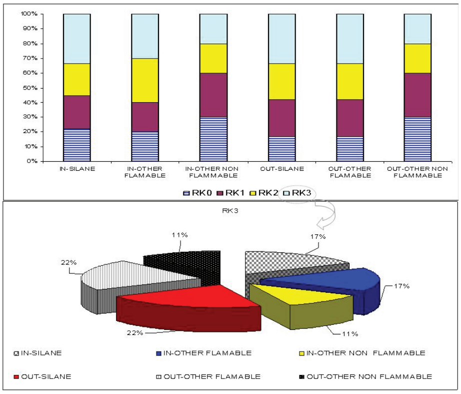


Figure 18. Main results of the PRA for photovoltaic manufacturing process showing the risk contribution of silane in comparison with other flammable and non-flammable substances. Non-flammable substances give the highest contribution to the low risk category RK0, while for the high risk category RK3 the situation is dominated by silane and flammable substances. The associated pie chart shows the detailed situation for the contributors to the category RK3.

- For non flammable substances there is a medium range risk both for releases before and after the process.
- The risk due to fire and explosions is dominant by comparison with other area events (flood or seismic).
- The barriers role and the intrinsic installation process role in managing risk challenges are dominated by the role of fire and explosions barriers. The detection systems, cleaning systems, and drainage systems are of medium range role in coping with the risk posed by various challenges. The intrinsic design features like preservation of leak-tightness and vacuum, support (electrical, control, etc.) systems and human errors are important tools to cope with high category of releases and medium level of risks.

5 CONCLUSIONS

The paper presents and discusses an innovative study which attempts to apply, for the first time, the PRA-based methodology in the field of the photovoltaic manufacture industry. Due to lack of data from existing PV installations, the model has been created in close relation with the nuclear environment, where this methodology is already of common use for safety management of nuclear power plants. Relying on proven PRA expertise and adopting data available from generic chemical industry databases could help where the information from PV area were not sufficient.

The results of this analysis show that it is possible to quantify the frequency of failures of the main processes leading to health challenges mostly affecting the occupational environment. The development starts with the identification of the possible scenarios, logically linked to particular end states through the development of event trees and fault trees.

Even if the information available from existing literature indicates that the probability of failures in the PV process are unlikely in comparison with other industries, especially due to the lower amount of chemicals involved in the process (Fthenakis 2003a), nevertheless the results highlight the existence of potential weak links along the production stream.

Such weak points could result in possible occupational health and safety threats to humans. In a complex system, such as a photovoltaic manufacturing installation, where many interconnected components dynamically function together, methods such as PRA can assist in consistently and systematically identifying interdependencies in order to assess potential risks throughout the entire life cycle of the installation (design, construction, operation and decommissioning).

Furthermore, the benefits of using PRA-based approaches, also in conjunction with other design tools, are clear when performing risk reviews before events happen. If applied in the PV industry, the use of the PRA method could offer a contribution to improve safety management systems in the manufacturing process.

Such an application would be in line with the best practice on these issues from other industrial fields (aviation, aerospace, nuclear, some other chemical processes).

REFERENCES

CCPS, 1989. Guidelines for Process Equipment Reliability Data. With data tables, *Center for Chemical Process Safety of the American Institute of Chemical Engineers, 1989.*

Council of the European Union 2007. Presidency Conclusions, *Council of the European Union, Brussels European Council, 8/9 March 2007.*

(ECN 2007). http://www.ecn.nl/publicaties/default.aspx?nr=ECN-E--07-026.

Fthenakis, V.M. 2003a. Overview of Potential Hazards, *Chapter VII in Practical Handbook of Photovoltaics: Fundamentals and Applications, T. Markvart and L. Gastaner (Eds.), Elsevier, 2003,* http://www.pv.bnl.gov/art_170.pdf.

Fthenakis, V.M. 2003b. Hazard Analysis for the Protection of PV Manufacturing Facilities, *3rd World Conference on Photovoltaic Energy Conversion, WCPEC-3, May 12–16, 2003, Osaka, Japan,* http://www.pv.bnl.gov/art_169.pdf.
NUREG2300. USNRC Guidelines for PRA
©Relcon Scandpower AB, 2008. RiskSpectrum® PSA Professional, *developed and maintained by Relcon Scandpower AB in Sweden,* http://www.riskspectrum.com/.
Serbanescu D., Colli A. & Vetere Arellano A.L., 2008. On some aspects related to the use of integrated risk analyses for the decision making process, including its use in the non-nuclear applications, *ESREL 2008 under issue.*
Serbanescu D. & Kirchsteiger C., 2007. Some methodological aspects on a risk informed support for decisions on specific complex systems objectives, *ICAP 2007.*
Serbanescu D., 2006. Some considerations on the risk analyses for complex systems, *SSR 2006.*