Environmental, Economic and Financial Uncertainties of Nuclear Electricity. A Closer Look at the Situation Worldwide and in Italy.

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ABSTRACT

The so-called nuclear *revival* worldwide is crashing against the Fukushima accident in Japan, as it already happened with the Chernobyl accident 25 years ago (1986). The Fukushima accident has pulled down the expectations and the active lobbying of the nuclear industry, claiming nuclear to be the solution to future world energy demand and increased concerns for climate change. We investigated the environmental impact, technical feasibility, nuclear fuel availability, market competition, financial risk and macroeconomic impacts of nuclear worldwide. The resulting picture, based on more than one hundred LCA literature studies worldwide, points out the existence of a large uncertainty on all the main aspects of the nuclear energy system, thus preventing the policy maker from relying on a stable and certain set of feasibility indicators. In spite of such uncertainty, the nuclear business industry was able to convince Governments and the public opinion in several countries that benefits were much larger than costs and expected risks. The consequences of the environmental, social and economic disruption in Japan, worsened by the combined effect of the earthquake and tsunami, are heavily affecting the world environmental and economic systems, thus making acceptance of nuclear energy even more unlikely. Countries who are already using nuclear electricity as well as those willing to move their first steps towards this direction (among which, Italy) will have to rethink their choices, under both the concerns of the public opinion and the reluctance of the business community to further support risky investments.

Keywords: nuclear energy, energy prices, uncertainty, Fukushima.

1. INTRODUCTION. THE NUCLEAR RENAISSANCE.

The first years of the new millennium were characterized by a renewed interest in nuclear energy (Adamantiades and Kessides, 2009), the so called "nuclear revival" (Owen, 2006). In developing countries thirty plants are in construction against the five in OECD countries (two in Europe: France and Finland) (ARPA, 2009; WNA, 2009). The Italian energy policy was also influenced by this interest wave, after the nuclear phase-out decided in 1987. This resurgence of interest was mainly based on claims that nuclear energy is cheaper, has lower price volatility compared to fossil fuels, it is secure in supply (Linares and Conchado, 2009) and does not contribute to climate change. The Fukushima accident placed an abrupt stop to nuclear industry expectations, forcing Governments to rethink their choices and energy plans.

1.1 The search for carbon free energy

Low nuclear GHG emissions is perhaps the most emphasized, studied and debated aspect. According to Sovacool (2008a), advocates of nuclear power consider it "the only non-greenhouse gas emitting energy source that can effectively replace fossil fuels and satisfy global demand". A 1000 MW_{el} coal power plant releases about 6 millions tons of CO_2 per year, while nuclear is claimed by its supporters to be quite CO_2 free. According to the international Nuclear Energy Agency (NEA, 2002) in the last 40 years nuclear has contributed to avoid 1,200 million tons per

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year of carbon dioxide. Opponents have objected that "nuclear plants are poor substitutes to other less intensive greenhouse gas generators": wind and hydroelectricity have respectively one-third and one-fourth less CO_2-equivalent emissions than nuclear power. The Oxford Research Group (Sovacool, 2008a) predicts that, assuming constant nuclear capacity, 2050 nuclear CO_2 emissions per kWh would equal those from gas fired power plants due to decreasing uranium ore grade.

1.2 Radioactive waste
The contribution to climate change is only a part of the story. Other relevant aspects include "high capital cost, proliferation of dangerous materials, nuclear terrorism, operation safety and radioactive waste disposal" (Toth and Rogner, 2006; Romerio, 2007; IAEA, 2008; Lenzen, 2010). Large amounts of nuclear waste have been accumulated in USA (Lior, 2006; Lenzen, 2010) and worldwide and there is no easy solution for radioactive waste disposal or destruction (Lior, 2008). No country has yet adopted a successful disposal after fifty years of nuclear civil programs. The first commercial geological repository is expected to open in Sweden by 2018 (ARPA, 2009); the solution to the nuclear waste issue (short-term and long-term nuclear waste management and spent fuel processing) is a prerequisite for further expansion of nuclear industry (Abu-Khader, 2009).

1.3 Market uncertainty
The actual competitiveness of nuclear must be analyzed in a wider perspective. It cannot only rely on the analysis of greenhouse gas emissions, since nuclear is a very complex and expensive technology and many more aspects come into play. The liberalization of electricity markets shows that the fate of nuclear is strongly affected by energy market structure. The loss of some main favorable conditions (governmental support, certainty of demand, a price regime based on recovering the production cost increase by charging higher prices to consumers, etc), lead to a drop of the number of nuclear plants built from 1990 to 2005 to only 1.7 nuclear plants per year (mainly in developing countries) compared to 17 nuclear plants per year built in the period 1970-1990 (ARPA, 2009). In liberalized electricity markets decisions about energy technologies are driven by the expected returns, taking into account the risks (afforded by the company, rather than by consumers as in a monopoly regime) linked to costs and revenues (Gross *et al*, 2009). Moreover, nuclear energy has to face new competitors such as renewable source technologies, characterized by a lower carbon content, better environmental footprint, increased population acceptance and higher growth rates favoured by cost reduction driven by technological innovation.

1.4 **The Fukushima accident**
The earthquake in Japan and the consequent ongoing melting of the Fukushima nuclear power plant reactors (6 reactors for a total power of 4,200 MW) have raised new questions on the fragility of the nuclear industry. Japan is no doubt one of the countries worldwide were the safety of urban and industrial buildings and plants was pursued with the strictest normative requirements and highest technical quality. The accident showed very clearly to the eyes of world that even such high performance was not a sufficient guarantee against the risks of human errors and natural disasters. The claimed low probability of a nuclear accident does not mean that it cannot happen (as it has always been suggested), and must be read differently: the disaster can happen, although not frequently. That the failure could be attributed to the conventional part of the plant (cooling pumps, emergency electric supply) makes the picture even worse, not better, since this makes it apparent that the safety of a highly risky technology depends on very conventional devices, designed for "normal" emergencies and therefore even more likely to collapse when huge natural disasters and crucial human errors occur.

The high Japanese standards of life demanded huge energy (mainly electricity) supply, in a country that has no local energy resources. The Japanese way of living will have to be re-designed towards a lower energy intensity of production and consumption patterns, with huge consequences on its national and worldwide economic systems. If nuclear energy becomes difficult or impossible to implement, then fossil fuels may become once again the main choice of industrialized and developing economies (with coal as the cheapest option). The likely increase of fossil fuels prices, hard competition for their supply as well as related environmental concerns, call for urgent, worldwide rethinking of standards of life, degrowth policies, and larger reliance on energy conservation and renewables. This is the major challenge that the whole planet is facing and nobody can predict at present if and to what extent this is likely to happen in the short or medium run.

2. NUCLEAR ENERGY. A WORLD OVERVIEW

About 440 reactors are presently in operation in 30 countries with a total installed capacity of 372 GW_{el}. Compared to fossil fuels, used in power generation, residential, commercial, industrial and transport sectors, nuclear energy is only used for electricity generation. Electricity from all sources has a market share of about 17.1% worldwide and 21.1% in OECD countries, in terms of final energy consumption. The nuclear share of world electricity supply during the period 1973-2008 increased from 3,3% (1973) to about 18% (1990), then decreased to 13.5% (2008) (De Paoli, 2008; IEA, 2010). Oil powered electricity declined its share from 24.7% (1973) to 5.5% (2008). Natural gas and to a lesser extent coal expanded their share in the same period (IEA, 2010).

Nuclear energy supplies about 34% of the total electricity produced in the European Union. Italy does not have nuclear plants in operation but imports about 15% of its electricity mainly from France, where 77% of electricity comes instead from nuclear (ENEA, 2009). The global nuclear electricity generation (except for China and India) was projected - even before the Japanese accident - to increase at rates lower than the overall electricity generation by 2030 (Lenzen, 2010). IEA (2008) foresees an installed capacity increase to 415-519 GW_{el} in 2030, EIA (2010) predicts an increase to 481 GW_{el}, and OECD-NEA projections predict up to 600 GW_{el} (Lenzen, 2010). Such a lower growth rate can be attributed to public concerns about safety, proliferation risks, restrictions in supply chains due to skilled labor shortage and insufficient enrichment capacity, lack of experienced contractors, lack of solutions for spent fuel disposal. According to Lenzen (2010) promises of performance improvement (higher resources sustainability, inherent safety, substantial reductions in radioactive waste volumes and lifetime) rely on the new generation-IV reactor and fuel cycle technology, foreseen by 2030. How these forecasts of nuclear development will be affected by the Fukushima accident and the need for increased safety devices and strategies is still to be seen, thus adding uncertainty to uncertainty.

2.1 Uranium market: a gap between demand and supply

The annual world uranium production has been around 50,772 t_U in 2009 covering about the 77.5% of annual demand (that is around 65,500 t_U) (WNA, 2010a). The gap between demand and production has been (and still is) met by secondary sources such as low enriched uranium (LEU) from the dismantling of nuclear warheads, re-enrichment of depleted uranium tails and spent fuel reprocessing (NEA, 2010). Two main periods of high uranium exploration can be identified. The first one, in the 1950s, was driven by the demand of weapon industry while the second one, in the 1970s, was due to the fast development of nuclear civil programs as a reaction to the 1973 oil embargo (Remme *et al*, 2007). Prices have been recently rising after about twenty years of decreasing trend (WNA, 2010a), thus stimulating new exploration activities and leading to an increased resource supply (Lenzen, 2010). World uranium Reasonably Assured Resources (RAR) and inferred resources were 3.2 Mt_U in 2003, increasing to 4.7 Mt_U in 2005, 5.5 Mt_U in 2007 (Lenzen, 2010) and finally 6.3 Mt_U in 2009 (D'Urso, 2010). RAR and inferred resources should provide uranium for the next 100 years at current production rates (Lenzen, 2010). Mudd and Diesendorf (2008) highlight that, despite perceived resource scarcity, the last two nuclear programs (nuclear weapon race in the 1940s and civil nuclear development in the 1960s) have been followed by new resource discovery. As with all fossil fuels, it is expected that the new deposits explored in the future will be deeper compared to most of the presently exploited deposits. The average ore grade mined is also expected to be lower as far as the best deposits are exploited, although Canadian newly discovered deposits show an increasing trend (Mudd and Diesendorf, 2008; Heinberg, 2009). A summary of world uranium producers is provided in Figure 1. It clearly appears that the uranium market is dominated by very few countries, similarly to the market of fossil fuels (and maybe even more).

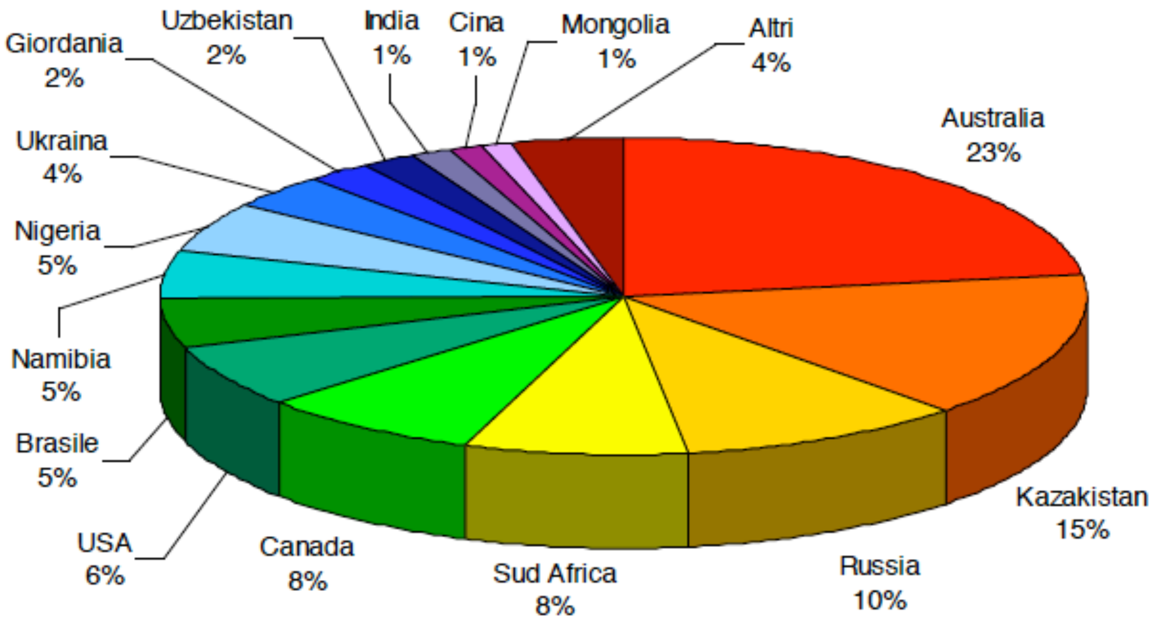

Figure 1. Overview of world uranium producers. (World Nuclear Association, June 2008)

2.2 A "peak" for uranium?

The gap between demand and supply of uranium raises concerns for a possible peak of world uranium (Figure 2). Compared to oil, uranium is relatively abundant but difficult to find at economically attractive concentration grades. The trend of production and the increase in price are signals of the gradual depletion of the best deposits and the need for exploiting new deposits that could require higher investments and extraction costs. Uranium is having the same trend as oil, where scarcity and increasing extraction costs are causing the so-called "oil peak". Some authors suggest that uranium is also near to or has already passed its peak (Bardi, 2006; Heinberg, 2009), although this trend is not easy to be confirmed because of the irregular production activities. The future of nuclear power will be heavily affected by either the scarcity of uranium resources and the increase of extraction costs, so that it might be very difficult to keep the promises of cheap nuclear energy, even without taking into account the cost increase determined by the demand for better technologies.

3. THE NUCLEAR FUEL CYCLE

Nuclear electricity is the final product of several upstream activities from mining to processing and finally converting the nuclear fuel. These activities, together with downstream disposal and processing of used fuel, constitute the nuclear fuel cycle (WNA, 2010b). A fuel cycle can, in turn, be classified into two types: "once-through" (open) and "closed". The latter types "reuse the nuclear materials extracted from irradiated fuel" (IAEA, 2009) while the former ones do not reuse nuclear materials and discharge them directly into disposal sites (Sovacool, 2008a). The choice between "open" or "closed" cycles is an important national policy decision (IAEA, 2009). At present most of the nuclear reactors operate adopting the "once-through" cycle (Owen, 2006; Sovacool, 2008a). Reactors operating with closed cycles, separate waste products from the still fissionable material, that is reprocessed and re-used. The reprocessing activity has the double advantage to reduce both the upstream demand for natural uranium and the downstream waste that must be disposed of (Lenzen, 2008; Sovacool, 2008a). Closed-cycle reactors have however disadvantages linked to the reprocessing costs, proliferation risks and problems with fuel cycle safety (Sovacool, 2008a).

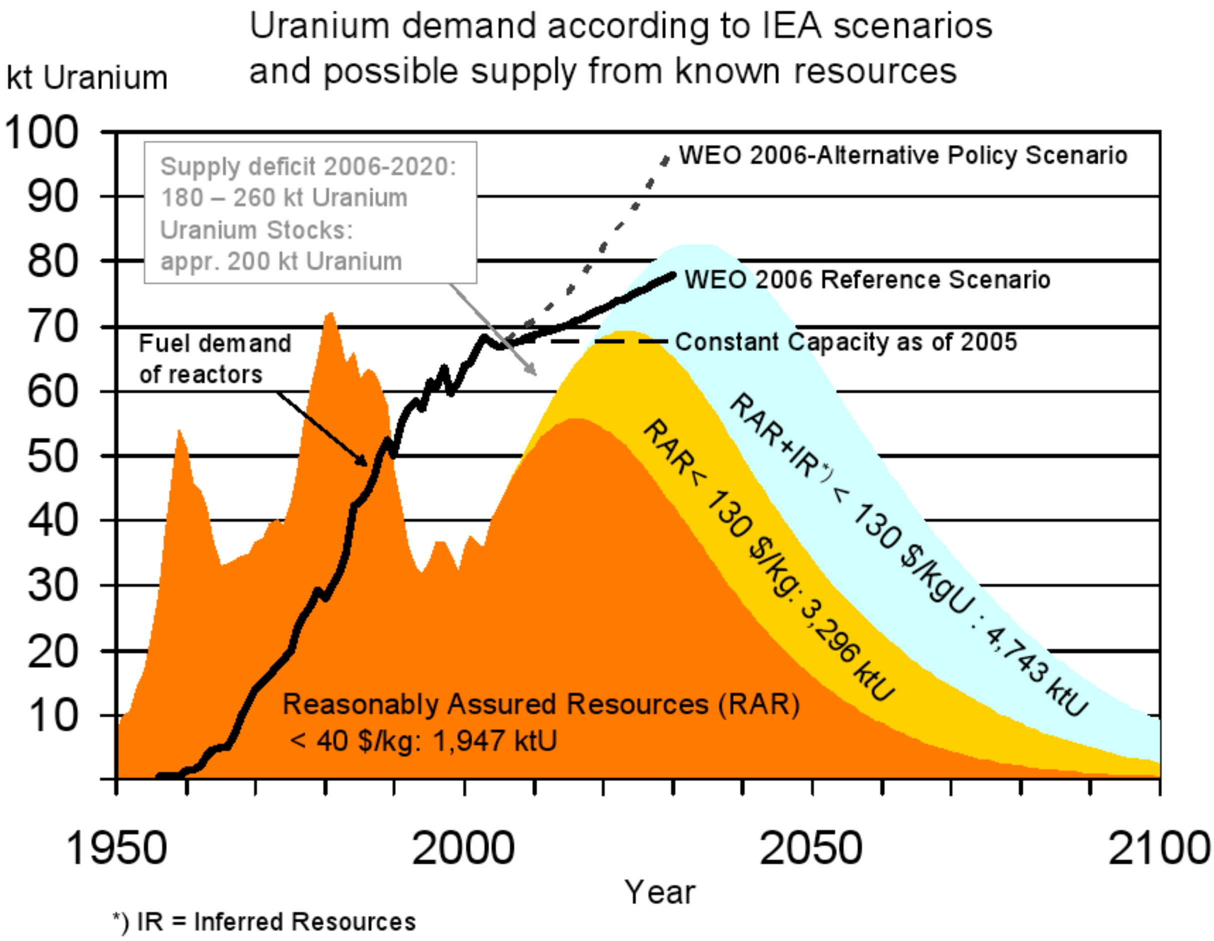

Figure 2. Estimates of available uranium stocks at different price compared to the present uranium demand for existing reactors. (EWG, 2006)

3.1 The five steps of nuclear cycle

The two nuclear cycle types share at least five interconnected stages (Figure 3): (1) upstream or "front-end" activities, in which uranium is extracted from ore (open pit, underground mining or in situ leaching), milled, converted to uranium hexafluoride, enriched and finally used to make the fuel element; (2) power plant construction; (3) plant operation and maintenance; (4) downstream or "back-end" activities, in which the spent fuel is conditioned, reprocessed and disposed in final repositories (if any); (5) plant decommissioning and mine site reclamation (Sovacool, 2008a). Other related activities (heavy water and zirconium alloy production) and transport of the materials among the different steps must also be taken into account (Owen, 2006; IAEA, 2009).

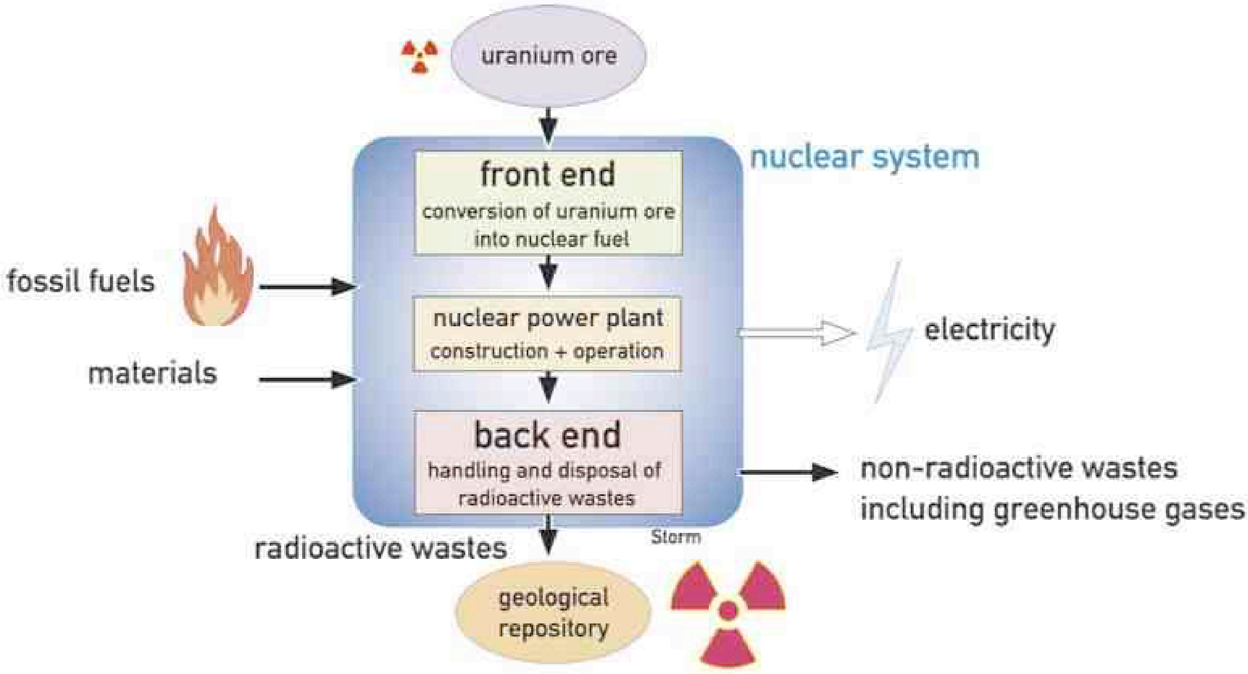

Figure 3. The nuclear fuel cycle (Van Leeuwen, 2006)

4. ENVIRONMENTAL ANALYSIS OF NUCLEAR ENERGY FUEL CYCLE

The present review is based on 9 LCA studies published since 2000, dealing with the nuclear fuel cycle at a different level of detail and scope. Four of them are actual LCAs of specific cycles (Lee *et al*, 2000, 2002; Dones *et al*, 2005; Wissel and Spohn, 2008), while the other five are in turn reviews of the existing literature (Gagnon *et al*, 2002; Fthenakis and Kim, 2007; Sovacool, 2008a; Lenzen, 2008; Fthenakis and Kim, 2009), making up for more than one hundred of cases compared and summarized.

4.1 Main focus on greenhouse gases

Most of the reviewed studies are focused on greenhouse gas emissions over the nuclear fuel cycle (Lenzen, 2008; Sovacool, 2008a) or on the comparison with other fossil or renewable energy cycles (Gagnon *et al*, 2002; Dones *et al*, 2005; Fthenakis and Kim, 2007). The latter also include indicators different than greenhouse gas emission, such as radioactive emissions (noble gases, H_3, C^{14}, aerosols, Actinides; Dones *et al*, 2005); SO_2, and NO_x emissions, and direct land requirements (Gagnon *et al*, 2002; Fthenakis and Kim, 2009), indirect land requirements (Fthenakis and Kim, 2009), energy payback ratio (Gagnon *et al*, 2002; Lenzen, 2008), and energy requirements (Lenzen, 2008).

4.2 Comparing CO_2 emissions from nuclear with other electricity generation processes

A comparison of the average CO_2 emissions from different types of power plants powered by either renewable and nonrenewable sources (Table 1) shows a very large range of options, with nuclear ranking low compared to fossil fuels and still high compared with wind, hydro and other renewables. The most surprising aspect in the reviewed studies is the large spread of estimates of CO_2 emissions from nuclear. Sovacool (2008a) calculates an average emission of 66 g CO_2/kWh_{el}, but due to the spread based on very different assumptions the real meaning of such an average is questionable and therefore scarcely useful for nuclear policy planning.

4.3 Dealing with uncertainty

Some authors (Fthenakis and Kim, 2007; Sovacool, 2008a; Lenzen, 2008) investigated the causes that contribute to the uncertainty of LCA estimates about nuclear GHG emissions in the literature. For Sovacool (2008a) the main reasons are: scope (e.g. some studies do not include all the stages of fuel cycle); assumptions about the quality of uranium ore (decreasing uranium grade in ore increases GHG emissions, as the lower the grade of uranium ore the higher the quantity of rock to be extracted and handled, the higher the energy needed and the GHG released); type of mining (methods of extraction and source of energy used for the extraction; for example uranium extracted closer to industrial centers releases less GHG emissions than the one extracted from mines in remote areas that rely on less efficient sources of energy); enrichment method (diffusion method is an older technology that requires much more energy than the centrifuge one); spatial focus (some studies assess emissions from specific reactors while others assess national and global average emissions based on industry data (individual cases in general provide a variety of estimates, while an average emissions approach always provides higher estimates); measurement of historical or marginal/future emissions (some of the studies refer to historical emissions while others look at future emissions for some type of plants, e.g. Dones *et al*, 2005); reactor type (the different design of reactor affects the GHG emissions: CANDU is considered by many as one the most GHG efficient commercial reactors); site selection (the location is a factor that in many ways affects a reactor's GHG performance; for example Canadian nuclear life cycles are associated to less GHGs than Chinese ones); operational lifetime (lifetimes and capacity factors vary in the reviewed studies yielding different estimates); the LCA applied (economic input-output based LCA, process-based LCA, and hybrid LCA have been applied, generating different GHG emission estimates; according to Fthenakis and Kim, 2007, the first method gives emissions 10-20 times higher than the process-based one). Lenzen (2008) identifies ore grade and enrichment method as the main factors that affect the energy and GHG performances in LWRs (also depending on the energy mix of the country), while only the ore grade affects HWRs, since the latter do not require enriched uranium. Fthenakis and Kim (2007) highlight enrichment, production and operation stages.

Table 1. CO_2 emissions from different typologies of power plant

Technology/fuel	Power/typology	Emissions range (gCO_2/kWh_{el})
Wind	2.5 MW, offshore - 1.5 MW onshore	9-10
Hydroelectric	3.1 MW, reservoir - 85 MW reservoir	10-12
Solar thermal	80 MW, parabolic	13
Biomass (short rotation, forest and waste wood)	Co-combustion with hard coal- steam turbine-reciprocating engine	14-41
Solar PV	CdTe-Polycrystalline silicon-CIS	19-70
Geothermal	80 MW, hot dry rock	38
Nuclear	300/1600 MW/Various reactor types	1-290
Natural gas	300-700 MW/Various combined cycle turbines	398-450
Geothermal	20 MW, hot water/wet steam field	380-650
Hydrogen from nat gas reforming	Fuel cells (stand alone or hybrid with gas turbine)	493-664
Diesel and Heavy oil	320 to 1280 MW/Various generators and turbine types	778-923
Coal	320 to 1280 MW/Various generators and turbine types	960-1100

Source: after Brown and Ulgiati, 2002; Dones *et al*, 2005; Fthenakis and Kim, 2007; Lenzen, 2008; Wissel and Spohn, 2008; Sovacool, 2008a; Ulgiati et al, 2010.

4.4 Looking out of the "global warming" boundaries

The potentialities of an LCA are related to the possibility to identify the most environmentally significant stages as well as the process contribution to more than one impact category. Providing a global picture of the environmental impacts, not only GHG emissions, is very important for transparent information to the society. In particular, out of the 9 studies reviewed, only Lee *et al*

(2000) and Lee and Koh (2002) carried out an LCA purposefully with these objectives as well as "to solve the problem when LCA is applied to facility releasing the radioactive wastes" (Lee *et al*, 2000). Their results show that the nuclear fuel cycle causes important environmental impacts also in other impact categories. Lee *et al* (2000) included in the study the upstream activities, the nuclear power plant, the waste treatment (once-through cycle) and all transportation steps. The functional unit was the delivery of 1 GWh of electricity from 11 PWRs in commercial operation in 1998 in Korea. The authors found that the main environmental impacts caused by nuclear fuel cycle were abiotic depletion) (73.3 g/yr), human toxicity through air (40.9 g-body Wt/yr) and global warming (27.7 g-CO_2/yr). They also identified mining and milling as the dominant stages in the cycle. These steps contribute to the largest depletion of abiotic resources (ADP) (96%), ecotoxicity through aquatic pattern (ECA) (98%) and human ecotoxicity through water (HCW) (78%). Lee and Koh (2002) applied LCA to three different nuclear cycle alternatives (once-through fuel cycle, with direct use of PWR spent fuel in CANDU reactor (DUPIC process) and recycling with plutonium and uranium recovery (PUREX process). The latter option resulted to be the less environmental loading. Internal exposure was identified as the most radiologically significant step.

Fthenakis and Kim (2009) focused on the life-cycle direct and indirect land use, measured as land transformation and land occupation, respectively for conventional and renewable sources. According to these authors, the electricity generation pattern that is less demanding in terms of land is nuclear (120-150 m^2/GWh_{el}), followed by coal (depending on the typology of mining: 100-900 m^2/GWh_{el}), photovoltaics (land demand 164-600 m^2/GWh_{el}, with potential of much better values in case of rooftop PV), natural gas (260 m^2/GWh_{el}), wind electricity (1000-2000 m^2/GWh_{el}), and finally biomass (12500 m^2/GWh_{el}). Gagnon *et al* (2002) estimated direct land use for renewables (hydro with reservoir, hydro run-of-river, biomass plantation, sawmill wastes, solar photovoltaic, wind power), coal cycles and nuclear. For nuclear they presented two values: without/with the land needed for the long-term waste. In the first case they estimated a value of 5000 m^2/GWh_{el}, a much higher value compared to other sources. In the second case the direct land requirement for nuclear increased to 100000 m^2/GWh_{el} (assuming that: "0.1 km^2/Wh_{el} is required for waste disposal, multiplied by 30,000 years, applied to 30 years of generation").

4.5 Lack of standardized procedures, lack of consensus

It clearly appears that the different assumptions, perceptions of Authors and evaluation methods heavily affect the final results in many ways, by providing different estimates or by disregarding some steps or impact categories. In spite of the standardized LCA procedure called for by ISO 14040/2006 and ISO 14044/2006 norms, with clear standardization requirements about boundaries, procedures, and impact categories, a large uncertainty is introduced into the set of results by a kind of reluctancy to compare on the same basis. In so doing, in spite of the large number of studies performed and reviewed, consensus about impacts was far from being achieved. Instead of providing a picture for informed decision making, lack of consensus add up to the uncertainty, raising an ethical question about the actual possibility to make a decision about nuclear, in the presence of uncertainty about costs and benefits. As the Three Mile Island, Chernobyl and Fukushima accidents have clearly shown, the potential consequences of an even unlikely accident are so catastrophic that they offset all the benefits to the economy and welfare that they might have provided before the accident. In business-as-usual times, the main benefits go to the investor, while the environmental burden and the risk is most likely transferred to the general public (radioactive waste repository, consequences of accidents on health and global economy, etc).

5. ECONOMIC AND FINANCIAL RISKS OF NUCLEAR POWER

Within the context of liberalization of worldwide electricity market the evaluation of investments plays a central role to complement the scientific debate (Holgner and Langlois, 2000; Adamantiades and Kessides, 2009; Linares and Conchado, 2009). Two economic and financial methodologies are adopted to this purpose: the consolidated Net Present Value (Rothwell, 1997, 2003; Greenpeace 2008) and the Real Option Value, considered more suitable for decision making in high and dynamic uncertainty contexts (Pindyck, 1993; Dixit and Pindyck, 1994; Holt *et al*, 2010). In both cases, risk analysis is one of the key tools to judge nuclear competitiveness as an investment option. From a strictly economic point of view three main risk factors are considered: (a) construction time, (b) investment costs and (c) variability of operating costs. Most of the existing plants have been built under a monopolistic regime, with governmental guarantees and controlled market prices, low capital costs and low investment risk (Owen, 2006). The investment risk, and the capital cost increased with deregulation of energy markets and were charged to electrical companies, penalizing capital intensive investments projects with long time return on investment and low technological flexibility (Romerio, 2007). Instead, investments in alternative power sources, be they combined cycle gas turbine plants and smaller renewable plants have been favored (Zorzoli, 2005). In such a context, investments on nuclear sector became uncertain and very variable. Considering a medium size nuclear plant (1000-1600 MW), construction costs are up to 10 or 15 times higher than those required for the construction of a natural gas plant (100-700 MW) per MW installed (Clò, 2008). The projected costs also tend to increase due to the extension of construction time (cost overruns) (Linares and Conchado, 2009). Finally, costs for nuclear plants decommissioning are estimated as about 25% of the original investment costs. The total costs of a nuclear plant can be splitted into about 60-75% *fixed* costs (capital repayments, interest allowed, decommissioning costs) and 25-40% *variable* costs (for instance, the cost of uranium and labor) (Owen, 2006). Unlike gas and carbon plants, the share of nuclear fuel cost on total production costs is relatively small (Owen, 2006; Lenzen, 2010). This is due to two factors: 1) the amount of uranium still available, capable to satisfy the present nuclear industry requirements (demand); 2) the nuclear reactor capability to store the uranium for a long time (Owen, 2006). As the fuel cost is low companies in OECD countries are trying to capitalize this advantage extending reactor working life. While the cost of electricity obtained from nuclear energy is not particularly affected by fluctuations of raw material price, other uncertainty factors related to security aspects, licensing, escalation of decommissioning costs (De Paoli, 2008), radioactive wastes disposal, might contribute to increase the financial risk perceived from private investors and, consequently, the level of expected return (Lenzen, 2010). The risks associated to the construction of a new nuclear plant reduce the international rating of the companies involved. Moody's suggests that after beginning the construction the downgrade risk increases sensitively (Moody's 2009). Therefore if a company is on category "A" before the plant construction, it could be downgraded to the "Baa" category (neither highly protected nor poorly secured) during the following 5-10 years, when the construction costs reach the peak and the main credit parameters are (lower) or negative. In this situation, within an inefficient credit market, it could be more difficult for the company to obtain further credit, while instead the interest rate and, consequently, the cost per kWh_{el} are likely to increase. Some authors (Sovacool, 2008b; Lazard, 2009; MIT, 2009;) calculated the levelized cost of nuclear electricity production, which is an international indicator of the average costs of electricity produced by a plant in one year. Linares and Conchado (2009) provide details of the shortcomings of this indicator in deregulated markets. Such a methodological approach takes into account *internal* costs (implementation, maintenance, fuel and operating costs) and *external* costs, both rather uncertain (De Paoli, 2008). According to a recent study (MIT, 2009) the levelized cost of nuclear electricity is 8.4 \$ cent/kWh_{el}, higher than the costs of coal (6.2 \$ cent/kWh_{el}) and gas powered electricity (6.5 \$ cent/kWh_{el}). Lazard (2009) provides higher estimates (nuclear electricity between 9.8-12.6 \$ cent/kWh_{el}, coal electricity between 7.4-13.5\$ cent/kWh_{el}, solar termal power between 9-10.4 \$ cent/kWh_{el}, Photovoltaics between 10 and 15 cent/kWh_{el}, wild electricity between 4 and 9 cent/kWh_{el}, and finally efficiency and energy conservation between 0 and 5 cent/kWh_{el}. Rogner and Langlois (2000) highlight that the future of nuclear power depends on the competitiveness strategies that industries, supported by technological innovation, will adopt to guarantee the economic and financial sustainability and reduce the safety risks. Such targets require strong political support to the nuclear industry. For instance, the problems related to waste disposal and safety involve suitable technological solutions and communication, able to achieve social consensus. Therefore, an energy policy which includes the use of nuclear power among its energy sources will have to handle three problems: overcoming the scarcity of public funds, choosing the best nuclear technology available, and finally conducting a cost-benefit analysis to compare nuclear with others renewable sources (Linares and Conchado, 2009).

5.1 The failure of statistics in risk assessment.

All the conservative figures provided above as well as economic and financial estimates carried out up-to-date can be highly questioned and made even worse by the consequences of the Fukushima accident on the Japanese and world economies. In spite of the claims that some accidents are highly unlikely, it cannot be denied that if they happen the consequences are very heavy. According to Stiglitz (2011), the "…wizards of finance…didn't understand the intricacies of risk, let alone the danger posed by 'fatal distributions' – a statistical term for rare events with huge consequences, sometimes called 'black swans'. Events that were supposed to happen once in a century – or even once in the lifetime of the universe – seemed to happen evert ten years. Worse, not only was the frequency of these events vastly underestimated; so was the astronomical damage they would cause – something like the meltdowns that keep dogging the nuclear industry."

The precautionary principle (UNESCO, 2005), dismissed and discredited by some as an emotional behavior, must become the guideline when making decisions with huge potential consequences, i.e. when dealing with the "emergence of increasingly unpredictable, uncertain, and unquantifiable but possibly catastrophic risks".

6. NUCLEAR ELECTRICITY IN ITALY.

6.1 First steps

Italy moved its first steps towards nuclear electricity in the year 1963, with the operation of a small gas-graphite nuclear reactor in Latina (160 MW) followed by two BWR – Boiling Water Reactors (Garigliano, 150 MW; Caorso, 860 MW), and a PWR – Pressurized Water Reactor (Trino, 260 MW). In 1988, as a result of the popular referendum held in 1987, after Chernobyl accident, the Italian Government decided to stop the nuclear energy generation. Moreover it blocked the construction of two new reactors in Montalto di Castro (2 x 1000 MWe BWR) and Trino (2 x 1000 MWe PWR), whose operation were planned to start in 1990. As a consequence of such decision, the four Italian reactors were stopped and the decommissiong procedure started (although slowly and still in progress). Only one small research reactor (1 MW) is still operative in the ENEA headquarters, Anguillara, Rome.

6.2 A nuclear-free country

The governmental decision following the referendum made Italy a country without nuclear energy, although surrounded by European nations which heavily rely on nuclear (France, Germany, Switzerland) and from which Italy imports electricity (Figure 4). A common claim of nuclear energy supporters is that Italy would not be safe anyway in case of major accidents in these countries. While this is certainly true, it should be rather read as a proof that decisions about nuclear must be jointly taken by all the interested countries not just by each country individually. This awareness calls for new forms of international laws and enforced control by international agencies, instead of advocating the dismissal of any forms of control while spreading sophisticated technologies in spite of population density, seismic hazard, and unlikely economic return.

Italy is therefore still free from major burdens related to radioactive contamination and the need for radioactive waste disposal. If we are going to undertake the nuclear roadmap and therefore modify the present condition, it must be supported by agreed upon decision, on the basis of clear evidence of benefits and costs.

Figure 4. Nuclear power plants in Europe (Google Maps, 2011).

6.3 Nuclear “revival” in Italy

The first official step to re-introduce nuclear energy in Italy after the phase out was the approval by Italian Parliament of the Enabling Act No. 99/23 July 2009. This Act, under the neutral title “Development and internationalization of enterprises, as well as miscellaneous energy issues” assigns to the Government the power to decide all the further steps for the reintroduction of nuclear energy, localization of power plants, the localization of the nuclear waste repository, and the choice of power plant typologies. The article 25 states that the activities related to nuclear energy must be considered activities of preeminent public interest and, as such, the final decisions will be made by the Ministry of Economic Development in agreement with the Ministry of Environment and the Ministry of Infrastructures, without any involvement of local communities and administrations. The same article foresees a campaign to inform the population “about nuclear energy, with special reference to its safety and economic benefits” (!). Finally, likely due to uncertainty about how populations may react to these “benefits”, the Article 39 foresees the possibility that some energy related plants are left under the direct control of the National Army or built within military areas”. A new referendum about nuclear will be hold on 12 June 2011, with the explicit goal of canceling most articles of the Enabling Act n. 99/23_7_2010 and previous related laws on the same topic.

6.4 Electricity demand and installed power

According to official data by TERNA, the society in charge for the electricity distribution in Italy (Terna, 2009: “Statistical data about electricity production in Italy”), the total installed power in Italy is about 105 GW. The peak demand of power was 57 GW in the summer 2007, and 52 GW in the summer 2009. As a consequence, it is not the installed power the problem, but instead the decrease of imported energy sources. Uranium, according to Figure 1, is also imported and therefore its use would not solve any dependence on foreign sources.

The total consumption of energy in Italy has been 320.3 TWh in the year 2009, about 5.7% less than in the year 2008. About 86% of such electricity is generated inside the country, manly based on thermoelectric power plants. The reason 14% electricity is imported is due to the fact that it is cheaper to purchase it at low cost mainly from France than generating further power internally. In fact, since nuclear plants cannot be switched off overnight, it is very profitable for France to sell the surplus (for less), in order to optimize its costs. Should the Government complete the construction of the planned four nuclear power plants (not yet started, anyway…), it would provide a maximum electricity production of 56 TWh, i.e. about 17% of total yearly electricity demand. The latter would be equivalent to about 12 MTEP, namely only about 6% of total national energy use.

6.5 Seismic hazard and population density

Italy is characterized by a higher seismic hazard than most European countries. Figure 5 compares the situation of Italy and the Balcanic area with the rest of Europe. It can be clearly seen that Italy – especially over the Appenninin mountain chain - is among the countries where the construction of nuclear power plants should absolutely be discouraged. Moreover, there are active volcanoes in the Tyrrenian sea, some of which under the sea and still active (Marsili, the Europe's largest undersea volcano), If eruptions would occur in this area, nobody could deny the possibility of large and destructive tsunamis, events that already occurred in the Tyrrenian area (ESPON, 2005).

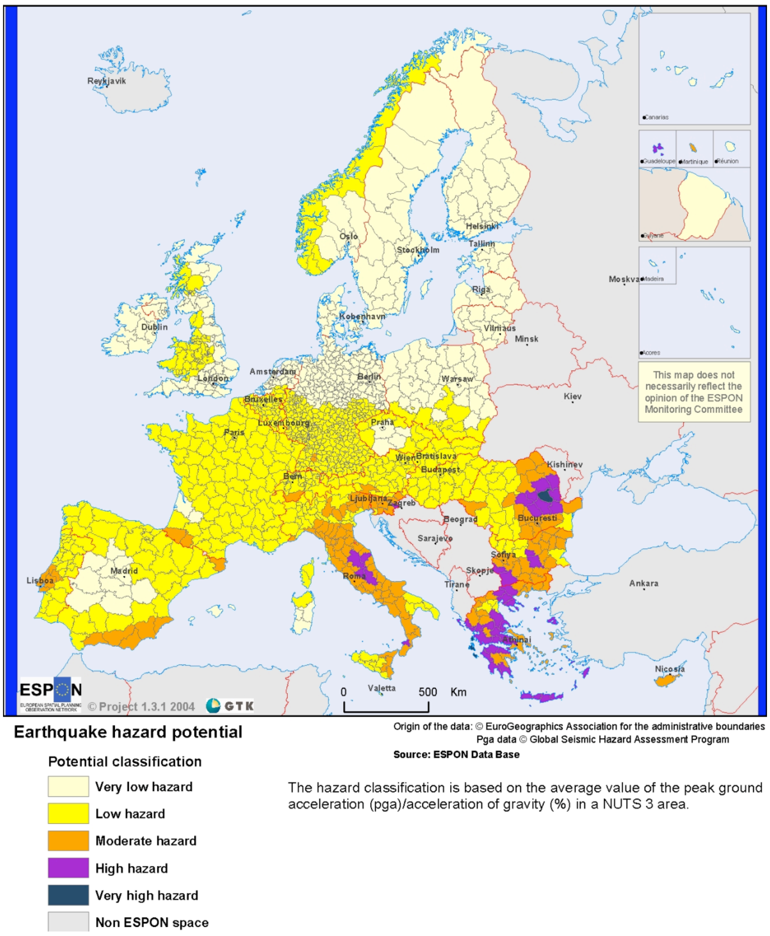

Figure 5. Seismic hazard potential of Italy compared to Europe (ESPON, 2004)

The potential consequences of a nuclear accident in Italy are made even worse by the fact that Italy is a high population density country compared to Europe. Figure 6 shows that most of the areas potentially candidate to host a nuclear power plant (Northern Italy, Tyrrenian coast, Puglia region, among others) are very densely populated compared to all other regions of Europe that already host nuclear plants. In case of accidents, much more people would be affected and it would be very difficult to evacuate them to safer areas.

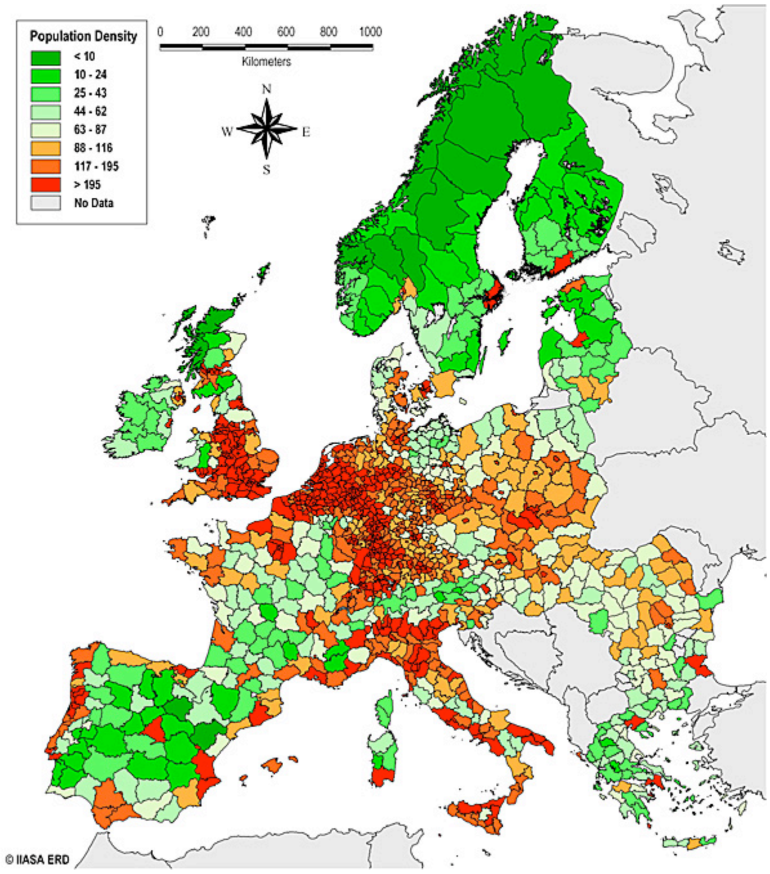

Figure 6. Population density of Italy compared to Europe (IIASA, 2002)

6.6 The potential for renewable energy

Finally, Italy is a country with huge renewable energy potential, especially solar insolation that could be used to develop photovoltaic electricity. Figure 7 shows the solar irradiation in kwh/m^2, much higher than in most parts of Europe. According to Figure 7, 1 kWp of photovoltaic power installed generates between 1200 and 1400 kWh, requiring in central-souther Italy 0.7-0.8 m^2 of installed module. The photovoltaic potential is already being exploited thanks to the feed-in tariffs of the so-called "Conto energia". Installed photovoltaic electricity was 0.7 GWp in 2009 and more than 2 GWp at the end of 2010 (and keeps growing). ". Wind power plants increased from 1.1 GW in 2004 to 4.9 GW in 2009.

After the Fukushima event, the Italian government decided a one year moratorium, in order to allow a pause for thought, while continuing to implement all the other actions and decisions that would allow, at the end of the moratorium period, to proceed speedily toward plants construction. In fact, the moratorium only extends to procedures related to the construction of new nuclear power plants in Italy, and will not affect ongoing work on procedures for the disposal of radioactive waste, including the construction of a national repository. The decision was criticized by the opponents to nuclear energy as a time wasting move, only aimed to weaken the anti-nuclear referendum scheduled for June 2011.

8. CONCLUSION

The picture that results from our review of more than one hundred studies worldwide as well as of the Italian situation concerning planned nuclear energy is a rather *uncertain* scenario about the majority of aspects of nuclear energy development, made day-by-day even worse by the news from

the Fukushima power plant, and the classification of the accident at the level 7, the highest possible risk level according to the International Nuclear and Radiological Event Scale (INES).
The future availability of suitable grade uranium is uncertain. Nuclear development scenarios seem to be associated to higher costs and prices than in the past. Shortages in the nuclear supply chain as well as the indefinite state of spent fuel worldwide could create additional barriers. Significant *uncertainties* are also linked to environmental impacts during normal operation (uncertain GHG emission estimates, scarce knowledge of the contribution to other impact categories), not to talk about the catastrophic consequences of accidents such as the meltdown in the Fukushima reactors; other uncertainties are associated to financial analysis (nuclear investment in competitive market is penalized compared to renewable sources and gas-fired generation, as it is characterized by high capital costs, long time return on investment and low flexibility; these factors contribute to increase the financial and economic risk for investors) as well as to macroeconomic analysis (it is uncertain the role that nuclear could have in addressing energy security; since gas-fired generation is the major competitor of nuclear in a cost-benefit perspective, the potential benefit of new nuclear is strongly affected by gas prices, carbon prices and nuclear costs).

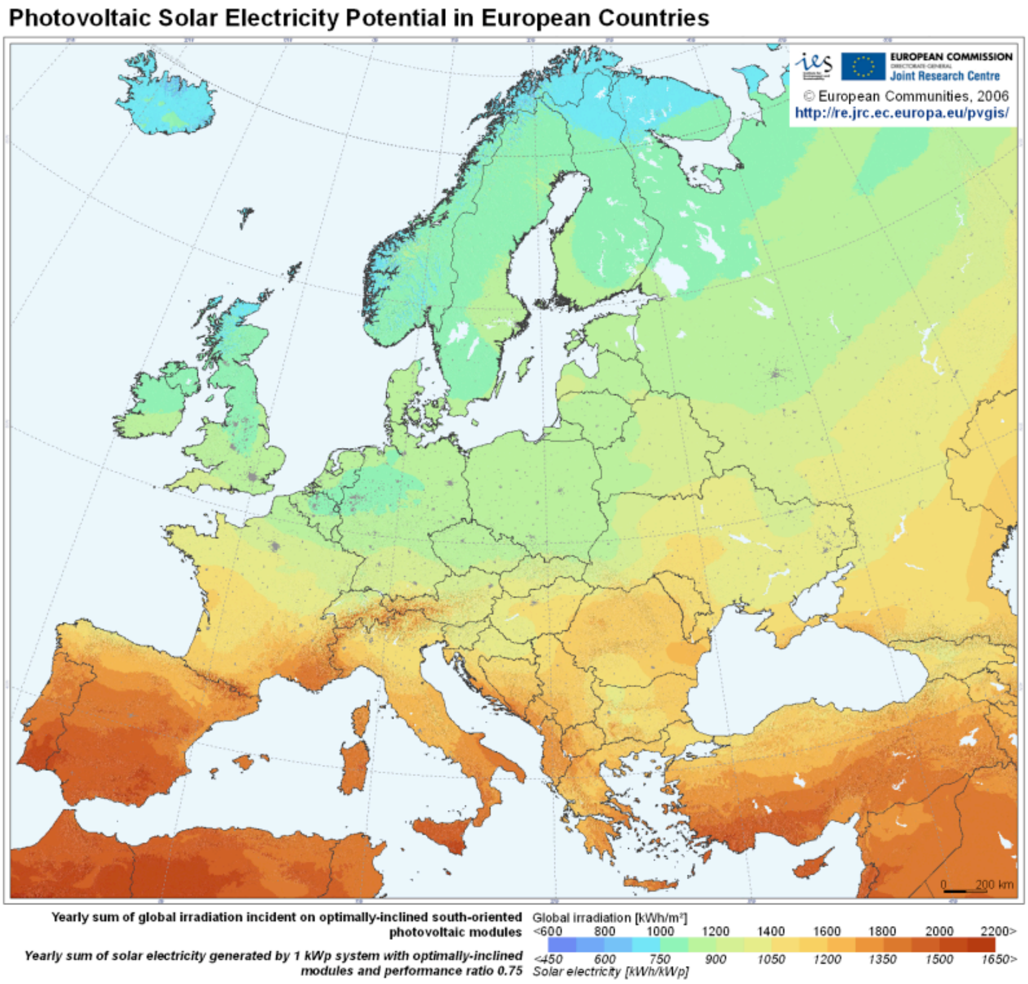

Figure 7. Solar insolation and photovoltaic electricity generation potential of Italy compared to Europe (Šúri et al, 2007)

The Fukushima accident made the uncertainty scenarios even worse, by adding the awareness of the catastrophic potential of "claimed unlikely" events. Finally, the evaluation of the Italian situation concerning energy policy, seismic hazard, population density, and solar insolation potential, adds up to the difficulty of understanding the real driving forces of the nuclear policy of the Italian government.

In the presence of such large and diverse uncertainties (and the only certainty of potentially disastrous events at times), a wise policy is not just “learning by doing”, nor even relying on expected “innovation” or “science results”. Choices may generate conflicts among equally legitimate interests, which call for participatory decision-making and planning. Once further and more reliable information is made available, the usual top-down decision-making process must be converted into a participatory procedure that involves all the stake-holders and the affected communities. In particular, when "facts are uncertain, values in dispute, stakes high and decisions urgent" (Funtowicz and Ravetz, 1991), the concept itself of “feasibility” must be converted from “technical and economical feasibility” into a more complex framework that includes aspects of “post-normal” science, namely the shift from the expert community to an "extended peer community" consisting of all those affected by an impact who are ready to enter into dialogue on it. They bring in alternate points of view, that include local knowledge and expertise not generally accounted for in normal scientific reports as the ones reviewed in this paper. It is not, therefore, a “to-do” list that should emerge out of such studies, but instead a call for multicriteria strategies and the awareness of the need for more complex evaluation tools and participatory planning.

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