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Nuclear and financial meltdowns: the impact of the Fukushima accident on the transition to a low-carbon economy

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Nuclear and financial meltdowns:

The impact of the Fukushima accident on the transition to a low-carbon economy

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Abstract

The paper is articulated in two parts. In the first part the consequences of the Fukushima incident are briefly described and analyzed offering a post-Fukushima reassessment of the advantages and disadvantages of nuclear power generation as compared to those of alternative energy sources. In the second part of the paper the intrinsic structural instability of the process of nuclear power generation is analyzed by comparing it with that of financial processes and showing that a thorough understanding of their critical dynamic nature puts serious constraints on their controllability.

The Fukushima accident made evident, and further worsened, the shortcomings of the existing energy system based on fossil sources. A crucial consequence was that it reduced significantly the current and prospective contributions of nuclear energy to the global supply of energy aggravating for a foreseeable future a trend characterized by structural excess demand of energy. A persistent increase in the price of nuclear energy and, more in general, in the trend of energy prices may frustrate any attempt to resume a sustained rate of growth within the business-as-usual paradigm. This calls for a more rapid transition towards a low carbon economy.

Key words: Fukushima accident, nuclear power generation, critical systems, structural instability, financial crisis, climate change policy, carbon prices, low-carbon economy

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1. Introduction

The Fukushima accident[1] had a great impact on the public opinion for several months but it is now almost completely forgotten. Mass media mention it either to mark its anniversary or to hint in a cavalier way to some of its disquieting persisting effects. The decommissioning of the plant is expected to require at least 3 decades but the procedure to stop the leakage of dangerous radiations is still unclear. In the meantime large amounts of water have to be pumped every day onto themolten cores of reactors to prevent further meltdowns so that each day an estimated amount of 300 tons of radioactive water flows into the Pacific Ocean (Cirincione, 2014). Moreover at least 50,000 people who lived near the Fukushima plants still cannot return to their homes due to high levels of radiation which continues to affect also local farming, cattle-raising, and fishing.Trace quantities of radioactive particles from the incident, including iodine-131and caesium-134/137, have since been detected around the world with serious consequences on the health of people. A study, for example, found that radioactive iodine from Fukushima brought about a significant increase in hyperthyroidism among babies in California (Mangano, Sherman and Busby, 2013).

In consequence of the silence of mass media and the reassuring attitude of governments and energy officials, the Fukushima accident's impact on the crisis, the energy policy and the transition to a low-carbon economy has been greatly understated in public debate. This accident, however, has significantly challenged the future prospects of nuclear power generation. First, the sudden swing of public opinion against nuclear power generation has led to a radical revision of energy policy in many states that is unlikely to be revised soon. In addition the necessary safety measures that will have to be taken to build more reliable plants and to manage them in a more prudential way has significantly increased the cost of

[1] For the sake of simplicity we mean by "Fukushima accident" the accident occurred in the Fukushima Daiichi (also called Fukushima1) plant in consequence of the Tohoku earthquake, and of the ensuing tsunami, that struck Japan on March 11 2011. We recall however that also the Fukushima Daini (or Fukushima 2) plant underwent in the same period an accident almost as serious. Its consequences have been encompassed by those of the Fukushima1 plant strengthening them in a significant way. For our purposes we do not need to analyse the specific contribution of the Fukushima2 plant to the consequences of the entire Fukushima accident.

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nuclear energy shifting investment towards alternative sources of energy. The nuclear lobby tried to resist the decline of the nuclear industry repositioning its communication strategy by emphasizing that nuclear power generation is not only «safer, cheaper and cleaner», but also «necessary to sustainability» (see for example the recent communication strategy of the World Nuclear Association)[2]. We cannot exclude that this point of view will eventually succeed to conquer again public opinion and policy makers, but in the absence of major technological breakthroughs, that to the best of my knowledge are unexpected in the near future, it is unlikely that a new "nuclear renaissance" may start soon. Following the Fukushima accident, the International Energy Agency halved its estimate of additional nuclear generating capacity to be built by 2035 (IEA, 2013).

The final impact of the Fukushima accident on the ongoing crisis and the transition to a more sustainable energy system is still uncertain but certainly highly significant. In any case the necessary upgrading of safety standards in nuclear reactors and the downsizing of their contribution to energy generation has been, and will continue to be in the foreseeable future, a significant factor of cost inflation that interacts with the ongoing recession jeopardizing a durable escape from it.

The paper is articulated in two parts. In the first part the consequences of the Fukushima incident are briefly described and analyzed. In section 2 a brief description of the Fukushima accident is laid out. The immediate reactions to the accident are summarized and appraised in section 3. Section 4 offers a post-Fukushima reassessment of the advantages and disadvantages of nuclear power generation as compared to those of alternative energy sources. In the second part of the paper the intrinsic structural instability of the process of nuclear power generation is analysed by comparing it with that of financial processes and showing that a thorough understanding of theircritical dynamic nature puts serious constraints on their controllability.[3] In section 5 and 6 I briefly describe respectively the nuclear chain reaction underlying the energy production in a reactor, and the financial "chain reaction" underlying the creation of exchange value in a monetary

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[2]The World Nuclear Association is the international organization that promotes nuclear power and supports the global nuclear industry.

[3] A draft of this part has been published in Vercelli (2014).

economy. In section 7 I discuss the analogies between the two chain-reaction processes from the point of view of their complex dynamics and the hard risks involved. Concluding remarks follow in section 8.

2. Description of the accident

The magnitude 9.0 Tohoku earthquake that struck Japan on March 11 2011, was the largest quake to strike the country and the world's fourth-largest earthquake in recorded history. This caused the largest nuclear disaster since that of Chernobyl in 1986, the only one with Chernobyl to measure the maximum level on the International Nuclear Event Scale: Level 7. The earthquake triggered a "scram" shut down of the three active reactors of the Fukushima plant. The ensuing tsunami stopped the backup diesel generators, and caused a blackout; the subsequent lack of cooling led to explosions and meltdowns in the active reactors. Only a prompt flooding of the reactors with the nearby sea water could have prevented the meltdown of their cores. However, this necessary intervention was irresponsibly delayed, apparently because it would have ruined the costly reactors permanently. It commenced thus too late only after the government ordered it (National Diet of Japan, 2012). The deliberate discharge of radioactive coolant water into the sea diffused radiation in it. According to a report published by the French Institute for Radiological Protection and Nuclear Safety, the emission of radioactivity into the sea was the most momentous ever observed (IRSN, 2012, p.107). Scientists monitoring sea life in the region have reported worrying observations. For example fish caught near the plant were found to have radiation levels more than 2,500 times beyond the limit established for seafood by the Japanese government (rt.com, 2013).

In the attempt of avoiding the meltdown of reactors' cores, the plant officials decided to vent the radioactive steam to reduce gaseous pressure but this immediately brought about a discharge of radiation in the atmosphere outside the plant. These late interventions did not succeed to prevent accidental or uncontrolled explosions and serious meltdowns in the three active reactors. According to official estimates of the Japanese government the total amount of radioactivity released into the atmosphere was no more than one-tenthof the

Chernobyl disaster. However the estimates have been later revised up to about ½ of the Chernobyl emissions by independent studies (MacKenzie, 2011). In any case the effects of radiation on the surrounding environment are worrying. For example butterflies captured near Fukushima have an unusual number of genetic mutations, and the deformities appear to increase through succeeding generations (Hiyama et al., 2012).

On day one of the disaster nearly 134,000 people who lived within 20 km from the plant were evacuated. Four days later an additional 354,000 who lived between 20-30 km from the plant were evacuated.

The earthquake and subsequent tsunami caused about 20,000 casualties. According to a Stanford University study by Ten Hoeve and Jacobson (2012), the radiation released is expected to cause about 180 cancer cases(the lower bound being 24 and the upper bound 1800), mostly in Japan. There were no immediate deaths due to direct radiation exposures, but at least six workers have exceeded lifetime legal limits for radiation and more than 300 have received significant radiation doses; radiation exposure to workers at the plant was projected to result in 2 to 12 deaths.

An additional approximately1600 deaths have been reported due to plant-related non-radiological causes such as mandatory evacuation due to disruption of local hospital operations, exacerbation of pre-existing health problems and extreme stress originated by dramatic changes in life. This led a few observers to question the government decision of a rushed evacuation of the Fukushima zone. However, according to some experts, in the absence of evacuation measures the long-term consequences on the mortality and morbidity of the local population could have been much worse (Ten Hoeve and Jacobson, 2012).

3. Immediate reactions to the accident and the likelihood of a new nuclear renaissance

In the decade preceding the Fukushima accident most citizens in many countries had turned favourable to an increasing share of nuclear power generation favoring what was then called with some exaggeration a "Nuclear Renaissance". After the accident great part of the public opinion turned against the use of nuclear power. A case in point was Japan itself where most people were favorable to nuclear power before the accident while immediately after the accident an Asahi Shimbun poll found that 74% wanted a nuclear-free Japan. In consequence of this change in public opinion the incumbent Prime Minister Naoto Kan announced a dramatic change of direction in energy policy promising to make the country nuclear-free by the 2030s; in the meantime the government forbad the construction of new nuclear power plants and introduced a 40-year lifetime limit on existing plants as well as tougher safety standards enforced by a new independent regulatory authority.

In March 2011, more than 200,000 people took part in anti-nuclear protests in four large German cities. In August the Government decided to shut down 8 reactors and to decommission the other 9 by the end of 2022. The Prime Minister Ms. Merkel made immediately clear the new point of view of the Government: "[we do not] only want to renounce nuclear energy by 2022, we also want to reduce our CO_2 emissions by 40 percent and double our share of renewable energies, from about 17 percent today to then 35 percent" (Merkel, 2011).

Also in Italy the growing acceptance of nuclear power observed in the first decade of the Millennium was dramatically reversed after the Fukushima accident as confirmed by the referendum of June 2011 in which 94% of votes have been expressed against the construction of new plants.

Even in France, where the nuclear power provides 75% of the energy required with a traditional substantial support of citizens, there was a significant change in the public opinion and then in government's policy. The government decided to cap the nuclear power generating capacity to the current level of 63.2 GWe, limiting it to the 50% of total energy output by 2025.

Switzerland, where nuclear power produces 40 percent of electricity, also announced a plan to shut down its nuclear plants once they reach a life span of 50 years taking the last plant off the grid in 2034.Also in the US the growing acceptance of nuclear power observed before the accident was eroded sharply by the accident slowing down and limiting the process of construction of new power plants.The 2008 projection of the Energy Information Administration of almost 17 gigawatts of new nuclear power reactors by 2030, was scaled back to just five in the 2011 projections.

Nuclear power plans were abandoned in many countries including Malaysia, the Philippines, Kuwait and Bahrain, or radically downsized as in Taiwan. China immediately after the accident suspended the pre-existing plan of constructing 25 new reactors to be added to the 14 already in service, providing a fivefold increase in nuclear-power generation capacity by 2020; however in late 2012 pre-existing plan was re-started though on a reduced basis.

We may conclude our brief survey of the reactions of different countries to the Fukushima accident by observing that the revision of energy policy in most countries has determined a significant reduction of the worldwide expected supply of nuclear power in the next two decades (see fig.1). As a consequence the share of electricity produced by nuclear power that was already declining before the Fukushima accident (from a maximum of 17% reached in 1993 to 11% in 2011) has accelerated its downward trend (see fig.2).

Fig. 1 and 2 about here

This does not imply, however, that we should project lightheartedly the current trend to an undetermined future. As a matter of fact, in the field of nuclear power generation we may detect a long-run cycle of fear similar to that observed in finance (see for the latter Minsky, 1982 and 1986). In the 1950s the fear of nuclear energy generation was widespread because it was an untried technology evoking the destructive potential of nuclear weapons but in the 1960 and 1970s the fear started to subside (apart from an active minority organizing impressive demonstrations).

The accidents of Three Miles Island (1979) and Chernobyl (1986) rekindled a widespread fear that relented only in the late 1990s and the first decade of the century leading to a sort of *Nuclear Renaissance* until the Fukushima accident. Should we expect a new phase of nuclear renaissance? No doubt, also after the Fukushima accident, the powerful nuclear lobby and its numerous supporters fought back to defend the future of nuclear energy obtaining some success in a few countries. In particular in Japan the new Prime Minister Abe elected on 26 December 2012 immediately said he was in favor of building new nuclear reactors. In the UK the program of trebling the total installed capacity of nuclear power generation by 2050 remained unaffected. At the same time, new nuclear projects are going ahead in some countries. This is true also of Russia that operates 31 reactors, is building 3, and has plans for another 27 while old reactors will be maintained and upgraded, including RBMK units similar to the reactors at Chernobyl. Russia has also begun building floating nuclear power plants that raised the interest of many emerging countries. In the USA there are plans for 13 new reactors, and two combined construction and operating licences for these were issued early in 2012 while five more are under review. Also China's downsized program is still very ambitious. Despite massive protests, India is also pressing ahead with a large nuclear program, as is South Korea.

Summing up, after Fukushima in most countries there prevailed a deep and extensive downward revision of nuclear energy policy. Many countries, including Germany, Italy, Switzerland and France, have stopped the construction of new nuclear plants. Most other countries have been downsizing the programs of construction of new plants including Japan and the USA. The aggregate effect at the world level is a drastic reduction of the share of energy expected to be produced by nuclear plants. Also the private industry started to withdraw from the sector of nuclear power generation. A significant case is that of the German-based engineering multinational corporation Siemens announcing in September 2011 its complete withdrawal from the nuclear industry, as a response to the Fukushima accident. In consequence of this decision Siemens ended plans to cooperate with Rosatom, the Russian state-controlled nuclear power company, in the construction of several nuclear plants in Russia over the coming two decades, shifting its investments to the renewable energy sector.

We may end this section by observing that, though the disruptions provoked by the subprime financial crisis and the ensuing Great Recession have not been inferior, the financial system and its regulation and supervision policies did not undergo so far a similar process of radical revision.

4. The advantages and disadvantages of nuclear power generation: a post-Fukushima reassessment

According to supporters, nuclear energy is a) *safer*, because the mortality and morbidity are argued to be significantly less than those with alternative sources, namely fossil fuels; b) *cheaper*, because the energy produced is claimed to be less expensive than that produced by renewables and non-conventional fossil fuels; c) *cleaner*, because thegreenhouse gases emitted are believed to be much less than those emitted by fossil fuels and other energy sources, being comparable to the case of renewables such as wind and solar power.

This paper is not supposed to survey the immense literature on the comparative evaluation of the pros and cons of alternative energy sources, but only to discuss what impact has been observed and may be expected in the near future from the Fukushima accident on the above claims. I wish to argue that there are little doubts that the latter had a significant impact on the first two claims. Therefore the burden of the pro-nuclear stance has shifted mainly on the third claim that is however, in my opinion, only partially true.

Let's briefly consider the first claim. The supporters of nuclear energy claim that the nuclear energy turns out to be safer than the alternative sources of energy (see fig.3).

Fig.3 about here

In particular a meta-study of the International Energy Agency published in 2002 (IEA, 2002) "put together existing studies to compare fatalities per unit of power produced for several leading energy sources. The agency examined the life cycle of each fuel from extraction to post-use and included deaths from accidents as well as long-term exposure to emissions or radiation.Nuclear came out best, and coal was the deadliest energy source"(McKenna, 2011). This and other studies correctly stress the heavy risks associated to the use of fossil fuel. For example fine particles from coal power plants kill an estimated 7,500 people each year in the US alone (Clean Air Task Force, 2014). In addition over 30,000 deaths have been attributed to US coal mining since the 1930s in consequence of mining accidents and respiratory complications (McKenna, 2011). In contrast to these estimates the International Atomic Energy and the UN estimate that the death toll from cancer following the 1986 meltdown at Chernobyl will reach a number not superior to 9000.

However, the belief in the relative safety of nuclear power as compared to that of alternative energy sources underestimates the number of casualties brought about by nuclear energy for a host of reasons. First, it is difficult to establish probabilistic causality even in the short run. Second, the official estimates often do not take into account the long-run effects of radiation on human health, failing to recognize that some cancers may take up to 40 years to develop while the genetic consequences may become visible after many generations. Finally it is even more rarely taken into account that "exposure to radiation may disturb a number of other biological pathways:cardiovascular and immunological disorders … psychological disturbances: stress… depression and suicides … pathological changes in reproductive function … Down Syndrome" (EEA, 2013, p.5). These important secondary effects are generally neglected also because, according to a controversial UN agreement, the IAEA has the right to veto any action by the WHO concerning health aspects of nuclear power (Karlsson, 2012, p.244).

The risks of nuclear power generation have been underestimated also because the accidents have been under-reported and played down. As a matter of fact, 100 major nuclear power plant accidents have been recorded since 1952, totalling more than US$21 billion in property damages.[4] Nuclear industry claims that new technology and improved oversight made nuclear plants much safer, but in fact 57 major accidents occurred since 1986. It is claimed that these accidents occurred in badly managed old-fashioned nuclear plants as in Chernobyl (1986); however two thirds of these accidents occurred in the US and the worst of all, the Fukushima disaster, in the technologically advanced Japan using state-of-the-art American technology (General Electric reactors).

[4] According to the definition adopted by the US federal government a major nuclear incident is one that either resulted in loss of human life or more than US$50,000 of property damage.

The French Atomic Energy Agency (CEA) itself admitted that technical innovation cannot eliminate the risk of human errors in nuclear plant operation.An interdisciplinary team from MIT estimated that,given the past record of nuclear incidents in power plants and the expected growth of nuclear power from 2005–2055,at least four serious nuclear power accidents would be expected in this period:in this view Fukushima is only the first of the series. We may conclude that nuclear energy may be safer than energy produced by coal but is much less safe than energy produced by clean renewable sources such as solar and wind plants.

Let us turn now to the claim that nuclear energy is cheaper. The favourable cost estimates produced by the nuclear lobby are criticized for not taking full account of the entire life cycle of the plant, the scarcity of fuel (high-grade uranium) exceeding that of cheap oil, the external diseconomies, the crucial role of an arbitrary high rate of discount utilized in the estimations.

In addition, after each nuclear disaster, the bar is set higher for safety. Reactors built after the disasters at Three Mile Island in 1979 and Chernobyl in 1986 cost 95 percent more than those built before the same occurred after Chernobyl and the same is likely to occur after Fukushima,also because the cost of plant construction was already increasing before the accident (fig.4). The cost of power generated in plants built after the Three Mile Island accident was 40 % higher, and after the Chernobyl accident it increased an additional 40 %. Most estimations performed in the period 2004-2009 were already showing that the cost of electricity produced in nuclear plants is higher than that produced by coal or gas (fig.5).

Figs 4 and 5 about here

Reserves from existing uranium mines are being rapidly depleted,and one assessment from the IAEA showed that enough high-grade ore exists to supply the needs of the current reactor fleet for only 40–50 years. Expected shortfalls in available fuel threaten future plants and contribute to volatility of uranium prices at existing plants. Uranium fuel costs have escalated in recent years,which negatively impacts on the viability of nuclear projects.

Let's turn now to the claim that nuclear energy is "cleaner". Estimates that take account of the entire life cycle of a nuclear plant, including its construction, its decommissioning, and waste disposal, find a much higher average level of greenhouse gases emissions than that reported from official sources. The meta-study by Sovacool (2010), research fellow at the National University of Singapore, finds the following average emission values: 66 gCO2e/kWh emissions for nuclear power, 960 gCO2 e/kWh for scrubbed coal-fired plants, 443 gCO2e/kWh for natural gas-fired plants, 32 gCO2e/kWh for solar photovoltaic, 10 gCO2e/kWh for onshore wind farms. He concludes that "for every dollar you spend on nuclear, you could have saved five or six times as much carbon with efficiency, or wind farms."

In the light of the analysis developed in this paper one has to conclude that the Fukushima accident made evident, and further worsened, the shortcomings of the existing energy system. It reduced significantly the current and prospective contributions of nuclear energy to the global supply of energy aggravating for a while the projected excess demand of energy. This effect is likely to last in the longer period since, in the absence of a major technological breakthrough, a new "nuclear renaissance", such as that occurred in the late 2000s, seems problematic, at least in the near future. To appraise the likelihood and desirability of a nuclear renaissance we have to understand the intrinsic structural instability of the process of nuclear power generation. To this end, in the second part of the paper, I provide a simple account of the complex dynamics underlying the nuclear chain reaction (section 5) and the credit chain reaction (section 6) showing in section 7 why it is so difficult to control critical dynamic processes of this kind and mitigate the hard risks involved.

5. The nuclear chain reaction and energy generation

The financial 'tsunami' that hit the USA and Europe in 2008 and culminated in the bankruptcy of Lehman Brothers in September 2008, triggered a 'meltdown' of the financial system that was somehow thwarted only by an unprecedented public bail-out of many big financial institutions.In March 2011, while the effects of the financial crisis were not yet fully re-absorbed, a real tsunami hit the County of Sendai in North-East Japan and triggered the partial meltdown of the nuclear reactors 1, 2, and 3 of the Fukushima1 plant. In my opinion, the analogies between these two episodes go much beyond mere terminology. Although the common features of nuclear and financial chain reactions have been almost completely neglected in scientific literature, I claim that we may draw from them pregnant insights.

I want to show in particular that, in order to understand and prevent catastrophic events in finance and nuclear energy generation, we have to focus on the critical chain reactions characterizing accident-prone systems. This sort of structural instability has to do both with the complex links between the parts of the system (as emphasized, among others, by Haldane and May, 2011; Johnson, 2011; and Lux, 2011) and with the complex dynamics of the system as a whole. A thorough analysis of critical dynamics should combine both aspects, but a full-fledged implementation of this promising research strategy needs more time than is left to avoid further catastrophes in the near future (Sornette and von der Becke,2011). This paper claims that the analysis of the dynamic properties of critical chain reactions in fragile systems may give important insights on their dynamics and controllability. This may be best shown through elementary models that avoid any confusion between complex and complicated dynamics. Simple models are sufficient to show that the processes characterizing nuclear reactors and finance dynamics are critical or structurally unstable, in the sense that an infinitesimal shock perturbing a critical process is sufficient to change radically the dynamic behaviour of the system (a critical survey of different notions of instability and their implications may be found in Vercelli1991). The stabilization strategy of these processes has proved so far unable to prevent a multitude of minor crises and the emergence of rarer deep crises leading to a 'meltdown'. This calls for a much more effective preventive strategy.

A nuclear meltdown is an informal term for a severe accident bringing about a, generally partial, melting of the nuclear reactor's core seriously jeopardizing the process of energy generation and its safety. The term is not officially defined by the Nuclear Agencies, such as the International Atomic Energy Agency (IAEA), but is commonly used by journalists and experts. In order to understand under which circumstances a nuclear meltdown may develop, we have to focus on the process of nuclear fission that occurs within the core of a nuclear reactor.

Both nuclear energy generation and nuclear weapons exploit the properties of nuclear fission. The nuclear fission is rooted in the high 'fragility' of the nuclides (or isotopes) of heavy elements such as Uranium (^{235}U) and Plutonium (^{239}Pu). When a heavy nuclide is hit by a neutron, it is likely to undergo a process of 'fission' that breaks the nucleus into two or more fragments, emits free neutrons and releases at the same time a great quantity of energy in the form of radiation (gamma rays and neutrinos) and heat. The most important fission reaction for nuclear energy generation are those of uranium-235; when it is hit by a slow-moving (thermal) neutron the following reaction occurs:

^{235}U + neutron $\rightarrow$ fission fragments + 2.4 neutrons + 192.9 MeV.

This reaction releases a huge amount of energy (hundreds of millions of eV, i.e. electronvolts, while chemical reactions release an amount of energy not exceeding a few eVs). In addition, if the ejected neutrons hit nearby heavy nuclides, they produce with a high degree of probability one or more further nuclear fissions. This may trigger a chain reaction that under given conditions may be self-sustained. A nuclear chain reaction is thus a formidable source of energy that may be used for civil purposes. The trouble is that it also releases a great amount of radiation, as the fission fragments are subject to radioactive decay while much of the energy released has the form of radiation (gamma rays and neutrinos). The difficult challenge of nuclear engineering is that of producing a great amount of energy in a continuous way without releasing radiation outside the nuclear plants. This is by no means an easy task, since the physics of nuclear plants shows how intrinsically unstable is the dynamic process of nuclear energy generation.

The crucial part of a nuclear reactor is its "core" consisting of an assembly of fuel rods. The core is usually surrounded by a neutron moderator (regular water, heavy water, graphite, and so on) that reduces the kinetic energy of newly produced neutrons in consequence of fission events since slower neutrons are more likely to induce further fissions. In addition, a nuclear reactor is typically characterized by an exogenous source of neutrons: a primary source that speeds up the start of a critical chain reaction or a secondary source that improves the convergence towards the critical state and its sustainability through time.

In order to study the chain reaction of a nuclear reactor the analysis has to focus on the population of free neutrons *N.* The first physicist who understood the possibility of a nuclear chain reaction and its huge implications was Leo Szilard in 1933: the language and the model used suggest that he drew inspiration from Kahn's multiplier model. This conjecture is plausible because he attended systematically lectures on economics with Von Neumann at the University of Berlin since 1929.

The dynamic behaviour of a nuclear reactor may be described in the simplest possible way by the following differential equation (Lewis 2008):

$$dN/dt = aN/\tau + N' \qquad (1)$$

where N is the number of free endogenous neutrons in a reactor core, N' is the number of neutrons injected in the core by an external source, τ stands for the average lifetime of each neutron before it escapes from the core of the reactor or is absorbed by a nucleus, while the parameter a is a constant of proportionality. In order to allow a more intuitive understanding of the complex dynamics of a nuclear reactor we translate this differential equation in a difference equation assuming that the length of the period is τ (so that $\tau = 1$). We get:

$$Nt = kNt\text{-}1 + N' \qquad (2)$$

where the parameters N' and k are assumed to be constant. In nuclear engineering the parameter k is called 'effective multiplication factor' and expresses the average number of neutrons released by one fission that bring about another fission. This number is crucial to study the dynamic properties of the core. When k<1, the system is *subcritical* and cannot sustain a chain reaction. In this case the system is stable, but the energy released rapidly fades away. The number F of fission events triggered by an exogenous neutron is given by $F=N'/(1-k)$, where $1/(1-k)$ may be defined as the 'multiplier' of exogenous neutrons that determines the equilibrium population of neutrons within the reactor. When $k>1$ the system is *supercritical* and triggers a chain reaction that increases exponentially the number of fissions and, thus, also the population of neutrons progressively amplifying the energy released and undermining its control. The chain reaction may be exploited for a sustainable production of energy only in the borderline case, when $k=1$. In this case the system is *critical* and the mean number of free neutrons remains constant bringing about, ceteris paribus, a stationary process of fission events and energy release. The only useful state of the core of a nuclear reactor is thus a bifurcation point that nuclear engineering tries hard to stabilize.

The dynamic behaviour of the reactor's core under the three different hypotheses mentioned above may be represented in a simplified way as in figure 6.

Figure 6 about here

We measure on the ordinates axis N_{t+1} and on the abscissa axis N_t. The equation (2) has a slope that depends on k, while the locus of possible equilibrium values (stationary since we have assumed that the exogenous neutron generation rate N' is constant) is represented by the bisecting line where $N_{t+1}=N_t$. The subcritical case represented in figure 1a is characterized by a stable equilibrium N^* that is a function of the rate of exogenous generation of neutrons:

$$N^* = N'/(1-k) \quad (3)$$

The supercritical case represented in figure 1c has no realizable equilibrium while the population of free neutrons and the number of fission events grows exponentially. In the critical case represented in figure 1b equilibrium is inexistent when $N'>0$ or indeterminate when $N'=0$. The critical case is a borderline singularity that is structurally unstable as an infinitesimal perturbation to k may transform the system in supercritical or subcritical (Vercelli 1991).

The fine tuning of k is very difficult, since the physical processes underlying the aggregate value of k are probabilistic and are subject to complex dynamics. The parameter k depends on the following main factors (Lewis 2008):

$$k = PiPfn - Pa - Pe \quad (4)$$

where P_i is the probability that a particular neutron strikes a fuel nucleus, P_f is the probability that the stroked nucleus undergoes a fission, *n* is the average number of neutrons ejected from a fission event (it is between 2 and 3 for the typical fuel utilized in nuclear plants: ^{235}U and ^{239}Pu); P_a isthe probability of absorption by a nucleus of the reactor not belonging to the fuel, and P_e is the probability of escape from the reactor's core. In other words, the product of the first three variables measures the strength of the fission chain reaction, while the probability of absorption and escape measure the average leakage from the system. In consequence of the probabilistic nature of its underlying process, *k* necessarily fluctuates off its critical value. When $k<1$ the efficiency in energy generation declines, when $k>1$ the safety of the reactor is undermined. A nuclear reactor thus requires reliable mechanisms of regulation that keep the average of the fluctuations of *k* at its critical value while constraining as much as possible their amplitude.

6. The propagation process in a monetary economy

A financial 'meltdown' is an informal term used in finance to designate a severe crisis that undermines the capability of the financial system to support the real economy, triggering a serious recession. This term is not rigorously defined in academic economics, but it is in common usage among practitioners, experts and journalists. This terminology has been probably imported from nuclear physics to emphasize a situation, similar to that of a nuclear meltdown, in which the financial system becomes unable to play its crucial role of support to the real economy, while the decision makers lose control of its dynamics. In this case, however, the metaphor should not be taken too literally, since a financial meltdown is typically characterized by a credit crunch and a sudden loss of liquidity: it is a freeze rather than a meltdown. In order to understand under which conditions a financial meltdown may happen we have to focus on the circuit of economic and financial transactions.

The economic activity is characterized by a mechanism of propagation of impulses that has several analogies with the nuclear chain reaction discussed above. While in a nuclear reactor the process of propagation of an impulse is based on the alternation between fission events of nuclides hit by free neutrons and the consequent ejections of free neutrons originating new fission events, in economics the process of propagation of an impulse is based on the alternation of income flows *y* received by economic units and their expenditure flows *e* financed by previous income flows. Focusing on the real side of the economy, the cumulative effects of this alternation triggered by an impulse *e'* representing the exogenous expenditure (autonomous investment plus public expenditure) converge towards a finite measure *y** when the marginal propensity to consume *c*< 1:

$$y^* = e'/(1- c), \text{ with } 0<c<1$$

where *1/(1- c)* isthe so called 'multiplier' introduced by Kahn (1931) and Keynes (1936) to study the effects of public expenditure and to determine aggregate income. Here *c* expresses the propensity of economic units to translate the inflows of income in outflows of expenditure and plays the same dynamic role of the effective multiplication factor *k* in the equations 2 and 3, describing the dynamic behaviour of a nuclear reactor. In this simple version of the multiplier model, the stability of the real system is assured by a positive marginal saving rate implying a net leakage from the system. The analogy with the subcritical case of a nuclear chain reaction is striking, as in both cases the propagation process has a similar dynamic structure (figure 7).

Figure 7 about here

A positive aggregate saving rate is the normal case observed in the past most of the time in most countries. However, in the last decades the saving rate greatly diminished in developed countries, progressively pushing the real economic system towards a critical regime, so reducing its stability. In a few countries, and most notably in the USA, the saving rate became slightly negative, or almost so (Guidolin and La Jeunesse 2007), just before the outbreak of the subprime crisis in 2007 contributing to the subsequent economic and financial instability. In addition we have to emphasize that the stabilizing role played by a positive saving rate crucially depends on the simplifying assumptions underlying the standard Kahn-Keynes multiplier model that all the investment is exogenous. This assumption restricts the validity of the model to the short period as the effects of income variation on the capital stock are neglected. The latter relation is usually expressed by 'the acceleration principle' or 'accelerator'. Its simplest version is the following:

$$I_t = v(Y_t - Y_{t-1})$$

where I_t stands for the induced investment and v is the capital/output ratio. As soon as we consider the impact of endogenous investment on the income-expenditure chain reaction, the potential instability of the process becomes evident, as has been first pointed out by Harrod (1939). When $I_t=S_t$ the aggregate endogenous expenditure E_t is equal to the aggregate income in the previous period Y_{t-1} and the system operates under a critical regime:

$$v(Y_t - Y_{t-1})= sY_t$$

from which we derive immediately:

$$(Y_t - Y_{t-1})/Y_t=g = s/v.$$

where $g=s/v$ is what Harrod called 'warranted', that is sustainable, rate of growth (figure 2b). Unfortunately this steady state is a critical dynamic path or 'razor's edge': an increase of expenditure over income, however small, would render the system supercritical determining an unsustainable rate of growth (figure 2c), while any reduction of expenditure would transform the system in subcritical (figure 2a). We do not pursue further this line of investigation from the point of view of the real economy, because the instability of the economy crucially depends on the financial side of the income-expenditure process. In a modern monetary economy, an excess of endogenous investment over saving in a given period is made possible by the credit system. In logical terms an excess of expenditure over income could be financed by dishoarding reserves accumulated in the past. However, hoarding and dishoarding had a crucial role in the ancient world, while accumulation and depletion of reserves have only a secondary role in modern capitalism. A persisting excess of investment over saving or, more in general, of expenditure over income has to be financed through borrowing. To understand the intrinsic dynamic criticality of contemporary financialised economies, we have thus to focus on the monetary and financial side of transactions and economic decisions (Minsky 1982, 1986; Kindleberger 1989; Vercelli 2011).

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The first monetary chain reaction that has been systematically explored in the economics literature is rooted in the "chain reaction" based on the alternation between credit and bank deposits. Additional credit translates in additional bank deposits that allow the concession of further credit and so on. According to the monetarists, this process explains the money supply M as exogenously determined by the monetary base B, assumed to be under the strict control of monetary authorities. The alternation mentioned above is characterized by a crucial leakage imposed by the legal reserve ratio α of banks while other two significant leakages are the excess reserve ratio β and the currency drain ratio γ. The credit multiplier may be thus expressed in the following way (Krugman and Wells 2009):

$$M = B(1 + \gamma)/(\alpha+\beta+\gamma)$$

The system is subcritical, since there is a leakage in the system represented by $(\alpha+\beta+\gamma)$ and the multiplication factor $1-(\alpha+\beta+\gamma)<1$; however, the lower the desired reserves $\alpha+\beta$ the more the system approaches a critical state. This is what happened in the recent years as financial innovation helped the financial institutions to elude the legal requirement, while the excess reserves ratio tended to vanish and the currency drain ratio became increasingly irrelevant. In the USA and other countries this tendency contributed to increase the instability of the system. The nexus between the credit multiplier and financial crises has been hinted at since long but never seriously analysed. For example Friedman and Schwartz observed that

"a liquidity crisis in a unit fractional reserve banking system is precisely the kind of event that triggers- and often has triggered- a chain reaction. And economic collapse often has the character of a cumulative process. Let it go beyond a certain point, and it will tend for a time to gain strength from its own development as its effects spread and return to intensify the process of collapse" (Friedman and Schwartz 1963, p.419).

In a fractional-reserve banking system, in the event of a bank run, the demand depositors and note holders would attempt to withdraw more money than the bank has in reserves, causing the bank to suffer a liquidity crisis and, ultimately, to perhaps default.

The monetarist belief in the exogenous nature of the monetary base fell in disrepute since the early 1980s. This assumption requires demanding conditions such as constant velocity of money circulation or at least its independence of the business cycle, while the empirical evidence suggests that it is quite volatile and strongly pro-cyclical. For example, Goodhart (1984, p.188) wrote that the base money multiplier model is 'such an incomplete way of describing the process of the determination of the stock of money that it amounts to misinstruction'. The credit multiplier has been rejected in particular by the advocates of an endogenous money theory advanced since long and subscribed among others by Schumpeter and many post-Keynesians (for a recent assessment see Lavoie,2003). Endogenous money theory states that the supply of money is credit-driven and determined endogenously by the demand for bank loans, rather than exogenously by monetary authorities. In this case, the analogy with nuclear reactor's instability is even stronger. The trouble with criticality is that, even in the absence of significant external shocks, a small change from within the system may be sufficient to trigger an unstable chain reaction. That is why criticality characterizes many catastrophe-generating systems (Sornette 2004).

In a given period *t*, each economic unit is characterized by a financial inflow y_t and a financial outflow e_t. The ratio e_t/y_t is a significant index of its current financial condition as it affects both its liquidity and solvency (Vercelli 2011). It is also an index of the financial multiplication factor. Its value may be easily higher than unity and may persist in such a state for a relatively long time. In this case, the dynamics of the financial system is supercritical, a 'bubble' in the economic jargon that typically occurs during a boom. This is made possible by credit that creates inflows *ex nihilo* in the expectation that the consequent increase in outflows will generate higher inflows in the future that will permit the repayment of debt with an interest. The increase in the extant credit of the private sector typically happens in a period of vigorous economic expansion, when the euphoria of the agents leads them to seek a higher leverage. As soon as the ensuing financial bubble bursts the system becomes subcritical to reduce the excessive leverage. Also in this case, as in a nuclear reactor, the critical state is the only one sustainable in the long run, while a deviation from it tends to increase progressively. In order to understand the sudden switch from supercritical dynamics to subcritical dynamics and vice versa, we have to introduce a second source of criticality that interacts with the first one. The current values of the liquidity ratio affect its expected values the sum of which determines the solvency of the economic unit. Whenever the solvency ratio *k** that measures the ratio of discounted expected outflows and inflows is <1, the unit has a positive net worth and is solvent; *k**=1 is the critical value beyond which the unit becomes virtually insolvent since its net worth is negative. To avoid bankruptcy, the economic units have a desired value of the insolvency ratio sufficiently far from the critical value to withstand unexpected contingencies. The interaction between *k* and *k** determines the cyclical behaviour of financial conditions (Vercelli 2011). This dynamic mechanism produces semi periodic minor financial crises during business cycles downturns and a few, much rarer, major financial crises that degenerate into recession or depression in consequence of contagion. To understand why, we have to add to the first chain reaction induced by the expectations, a second chain reaction that depends on the financial linkages between units (Haldane and May 2011; Lux 2011). In minor crises the contagion is limited in extent, time and space, while in the major crises its effects are pervasive and quite difficult to stop.

7. Nuclear and economic chain reactions: analogies and implications

The chain-reaction criticality characterizing the dynamics of a nuclear reactor and a monetary economy raises similar issues of regulation and risk management. First, criticality implies that predictability and controllability are severely limited and active regulation is arduous and unreliable. In nuclear reactors the principal instrument of regulation is given by control rods that may be inserted, to variable degree, in the core of the reactor to slow down the chain reaction as soon as it becomes supercritical or to accelerate it as soon as it becomes subcritical. In the economy the chain reaction may be slowed down and moderated by reducing the leverage of economic units and improving their solvency indexes. However, while successful regulation is manageable in both cases under routine circumstances, it may become prohibitive under unexpected scenarios. The regular working of the reactor is constantly monitored by highly trained technicians. They may, for example, insert control rods to reduce or increase the effective multiplication factor *k*. Unfortunately these active interventions of regulation are subject to errors that can trigger an uncontrollable process, leading to the partial meltdown of the core of nuclear reactors. Serious mistakes have been made quite often even by the best trained technicians being unable to forecast the complex dynamics of a nuclear reactor following an unexpected event (that does not need to be a large shock to have huge effects). That is why the training of nuclear plants technicians includes an extensive programme of simulations to refine their ability to cope with unforeseen circumstances. It is impossible, however, to simulate all the possible scenarios and the risk of inadequate behaviour remains extremely high. The Chernobyl accident, for example, has been triggered by an incautious stoppage of the reactor 2 to perform a test meant, ironically, to improve its safety. Analogously, the subprime crisis has been triggered by systematic and reiterated misbehaviour of many subjects, including the over-exposition of financial institutions and households, the illusion that structured securities could spread risk in a more efficient way, the lax supervision of monetary authorities reluctant to interfere with private decisions. The intrinsic weakness of active regulation in these two fields has led the experts to focus on mechanisms of "passive" regulation that are automatically switched on in case of necessity. In nuclear reactors the principal mechanism of passive regulation is provided by the neutron moderator (often regular water) surrounding the fuel bars. The controllability and safety of nuclear energy generation depends crucially on the amount and nature of the neutron moderator. There is an optimal amount for any given kind of moderator, as less moderation reduces the probability of fission while more increases the probability of escape. In addition most moderators become less effective with increasing temperature, so that if the reactor overheats the chain reaction tends to slow down. For example, when regular water, that is used as moderator in most reactors including those of Fukushima, starts to boil the effective multiplication factor is significantly reduced. However, there may be an unexpected leakage of water or steam, as well as a failure of the system to pump new water into the reactor's core as in the case of Fukushima1 after the flooding of the emergency pumps. In the economic system passive regulation is delegated to the invisible hand of the market. However, only in the case of an ideal model of perfect-competition we may rely on market self-regulation (Arrow and Hahn, 1971). Unfortunately, real markets do not comply with the long list of demanding assumptions that define a perfect-competition market so that the 'invisible hand' is often weak, trembling, and coerced by big companies or public agencies. In real markets, as in existing reactors, the failure of self-regulation may originate a cascade of further failures that may bring about their 'meltdown'. In both cases, the likelihood of local failures that may have much wider, even global, consequences calls for a global regulator that imposes strict standards to local units and has the power to enforce them. This is neither the case in the nuclear energy field nor in economics and finance. In both cases the authorities are national and the efficiency of their interventions is jeopardized by local interests and regulatory capture (Tanter, 2013).

The structural instability characterizing the nuclear and financial processes has been recognized by supervisors and regulators in both fields by applying stress tests to nuclear plants and banks to ascertain their vulnerability to shocks. In particular all nuclear power plants in the EU underwent stress tests and peer reviews in 2011 and 2012. Many other countries adopted the EU stress-test model for nuclear plants(including Switzerland and Ukraine, Russia, Turkey, Armenia, Taiwan, Japan, South Korea, South Africa and Brazil).Analogously the European Banking Authority (EBA) started in 2009 (and repeated in 2010, 2011, and 2014) the EU-wide bank stress test exercise to ascertain the vulnerability to shocks of the main EU credit institutions. The adoption of stress tests in the case of nuclear plants and banks recognizes implicitly the structural instability of the nuclear power generation process and of the financial activity, a sort of instability that can be probed only through simulations under predetermined scenarios.In both cases, however,the stress tests may be useful to understand some of the fault lines in the system but are intrinsically unreliable since they can only simulate the effects of a given category of shocks in a given scenario and not of all the possible shocks in all the possible scenarios. The shocks that are unexpected ex ante may be the most dangerous. In the case of a nuclear plant how can we simulate the effects of a meteorite, or aterrorist attack, or of anuclear weapon? In the case of the financial system, its evolutionary nature makes the prediction of possible shocks necessarily incomplete.

8. Concluding remarks

I concluded the first part of the paper by observing that the Fukushima accident made evident, and further worsened, the shortcomings of the existing energy system based on fossil sources. A crucial consequence was that it reduced significantly the current and prospective contributions of nuclear energy to the global supply of energy aggravating for a foreseeable future a trend characterized by structural excess demand of energy. This effect is likely to last in the longer period since, in the absence of a major technological breakthrough, a new "nuclear renaissance" such as that started in the late 2000s seems unlikely and undesirable in the near future. Simple improvements of the existing technology would be insufficient to guarantee safety "... because most nuclear power plants have been adapted from reactors developed for military applications...the nuclear industry should seize the opportunity [given by the Fukushima accident] to cut the umbilical cord with its military origins once and for all" (Editorial New Scientist, 2011, p.5).To be more specific in the light of the preceding analysis, I may observe that the ease of triggering a supercritical process is crucial for a nuclear weapon but is deleterious for power generation. This problem could be circumvented by using a different fuel (such as thorium) much more stable than uranium and plutonium (Shiga, 2011). However, the implementation of an untried technology takes time.In the meantime the impact on climate change of the Fukushima accident will continue to be negative ifthe missing supply will continue to be filled by a further use of fossil sources: mainly coal, as well as unconventional oil and shale gas that cause massive emissions of greenhouse gases and other severe negative externalities.

This structural change in energy supply is likely to extend its effects much beyond the boundaries of the existing energy system, deeply affecting the likelihood of a durable escape from the great recession and of a new phase of steady growth. A persistent increase in the price of nuclear energy and, more in general, in the trend of energy prices would trigger and sustain a process of cost inflation liable to accelerate significantly as soon as the worldwide rate of growth of GDP starts to acquire momentum. The ensuing likely increase in the rate of interest engineered by central banks to prevent inflation in the real sector is likely to choke off any attempt to resume a sustained rate of growth within the business-as-usual paradigm.

On the other hand in consequence of the effects of the Fukushima accident the energy from renewables has become cheaper in relative terms. This provides an opportunity for accelerating the transition towards a low carbon economy as the change in the relative price of energy sources may encourage a massive shift of investment from nuclear and carbon energy to renewable energy. However, though I do not think wise to advocate a nuclear renaissance unless the effective implementation of major technological breakthroughs suggest a revision of this opinion, there is some ground to suggest that the escape from nuclear energy should not be too rushed to avoid a spike in greenhouse gases emissions.

In the second part of the paper I argued that a new "nuclear renaissance" is unlikely and undesirable in the proximate future.The risks involved in nuclear energy generation are not just a matter of faulty design of a nuclear reactor as they are intrinsic in the complex dynamics of the underlying chain reaction even when active and passive regulation seem to be carefully designed. Analogously, the risks involved in sophisticated financial systems spring not only from the fraudulent or myopic behaviour of 'rotten apples', as has been often maintained, but mainly from the in-built criticality of financial processes. We have to understand that the frequent occurrence of nuclear accidents and financial crises are both deeply rooted in the structural instability of their underlying processes, and that a correct management of the hard risks involved by their complex dynamics requires the adoption of precautionary policies much more rigorous than the current ones (Vercelli 1998).

I hope that the analysis started in this paper may be further pursued to assess the hard risks involved by fragile accident-prone critical dynamic systems such as nuclear reactors or financial systems.

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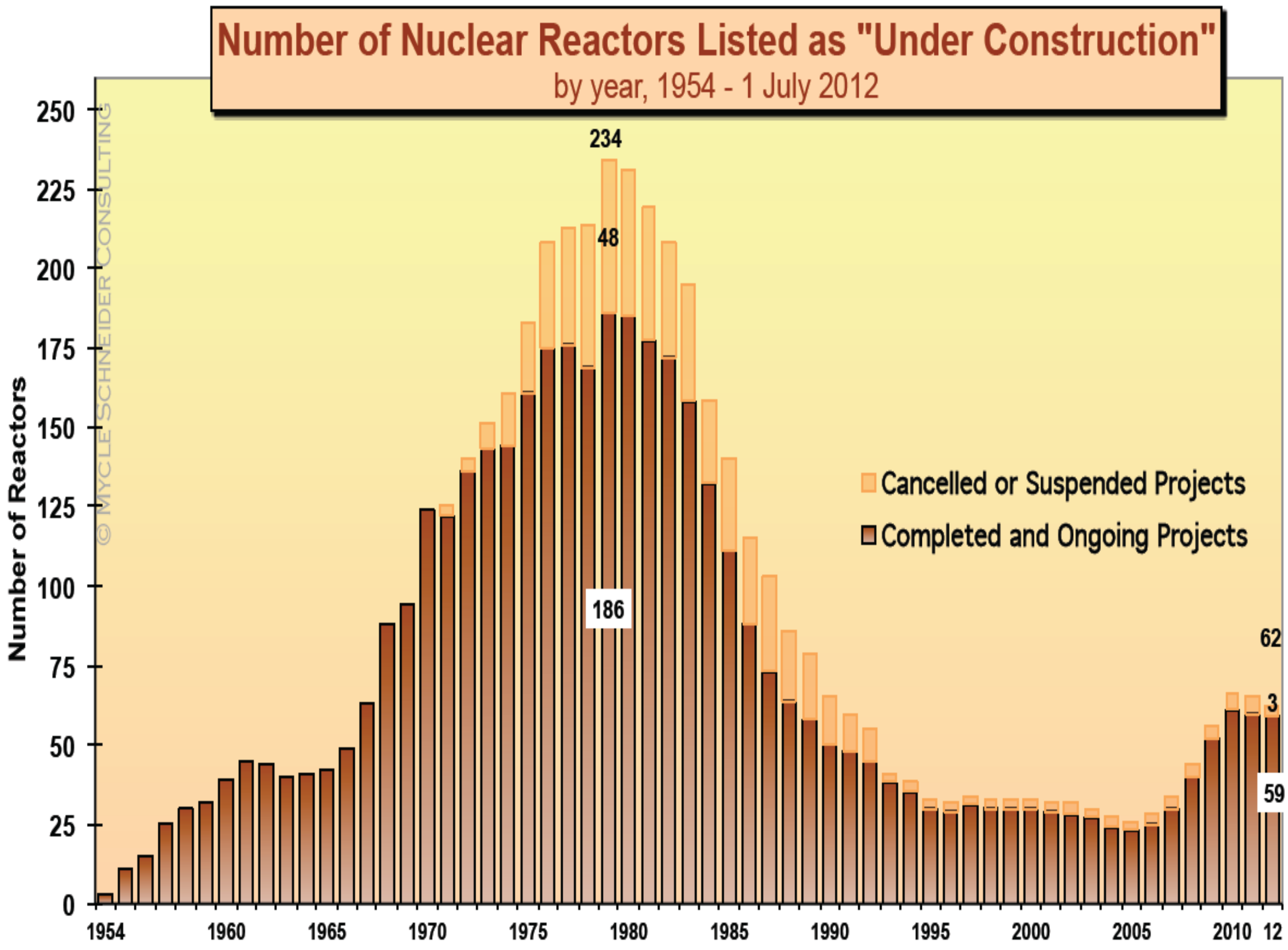

Fig. 1 Number of nuclear power plants under construction

Source: IAEA-PRIS, MSC 2012 (figure 5 of The World Nuclear Industry Report 2012)

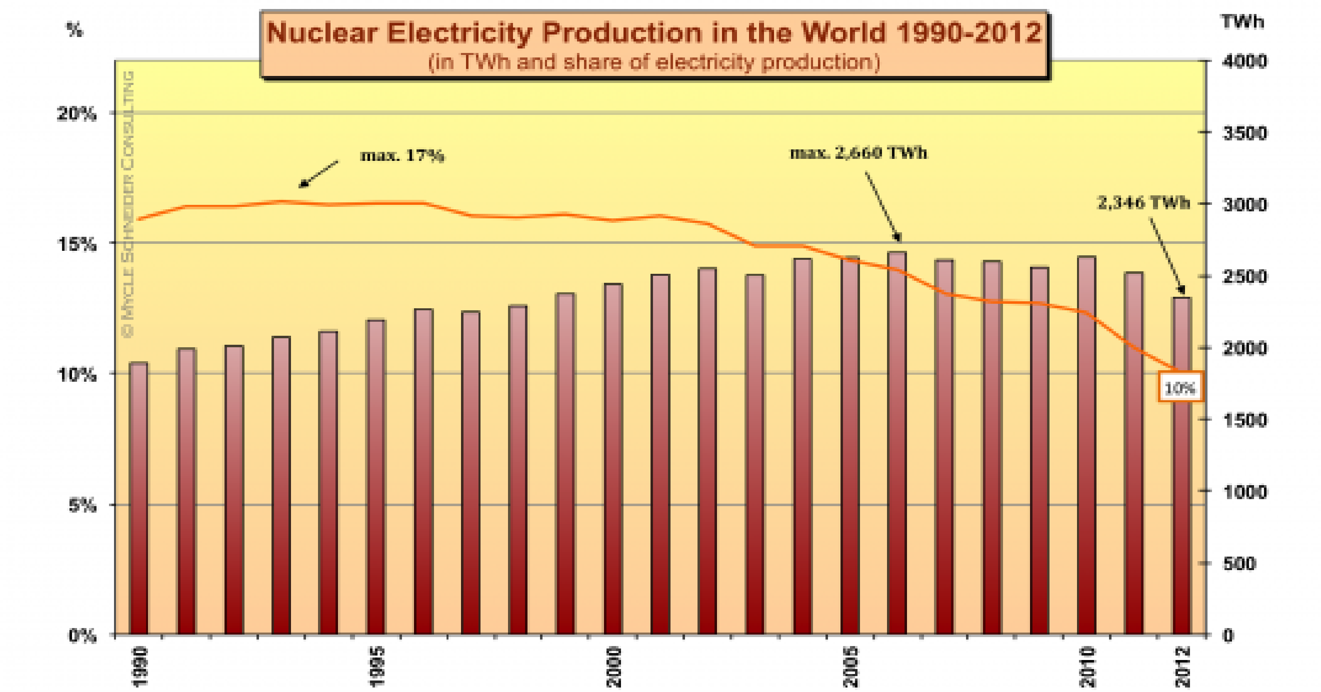

Fig. 2Nuclear electricity production and share

Source: Source : IAEA-PRIS, BP, MSC, 2013

(figure 1 of The World Nuclear Industry Report 2013)

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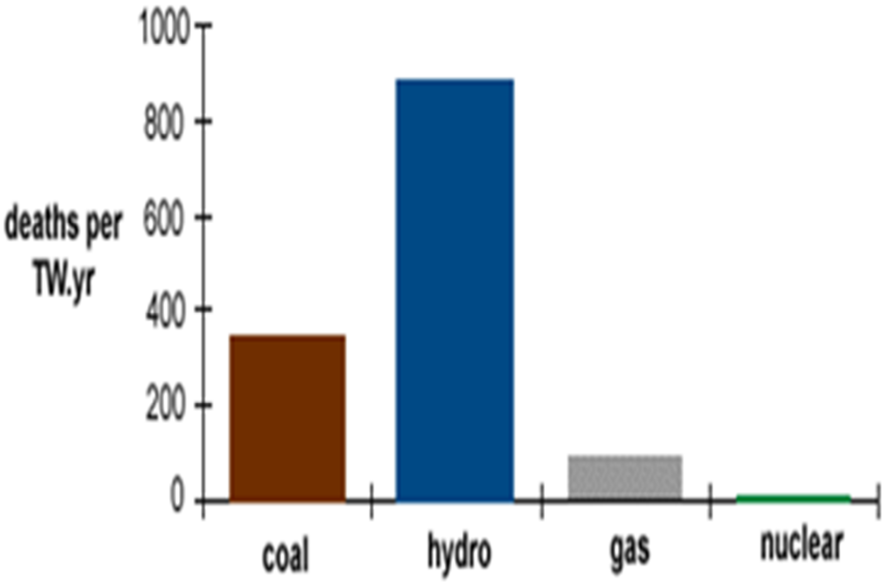

source: Paul Scherrer Institut 1998, considering 1943 accidents with more than 5 fatalities.
One TW.yr is the amount of electricity used by the world in about 5 months.

Fig 3Deaths from energy-related accidents per unit of electricity

Source:Hirschberg, S., Spiekerman, G., and R. Dones, 1998, Paul Scherrer Institute

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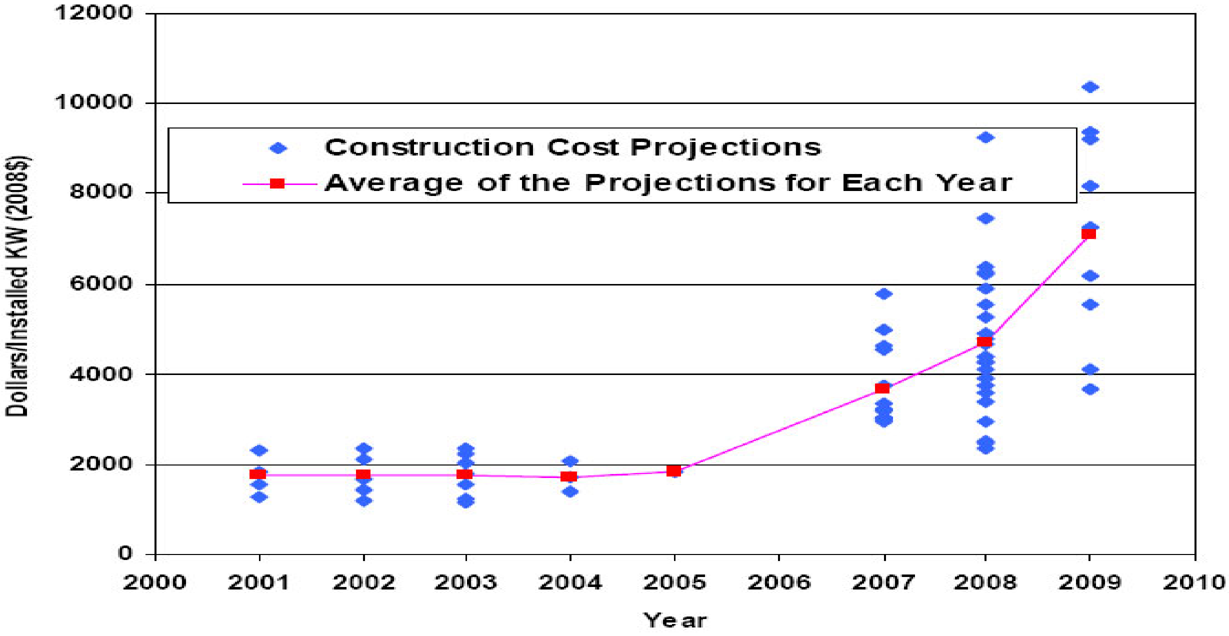

Fig.4Construction costs of new nuclear plants

Source: Sokolski, 2010

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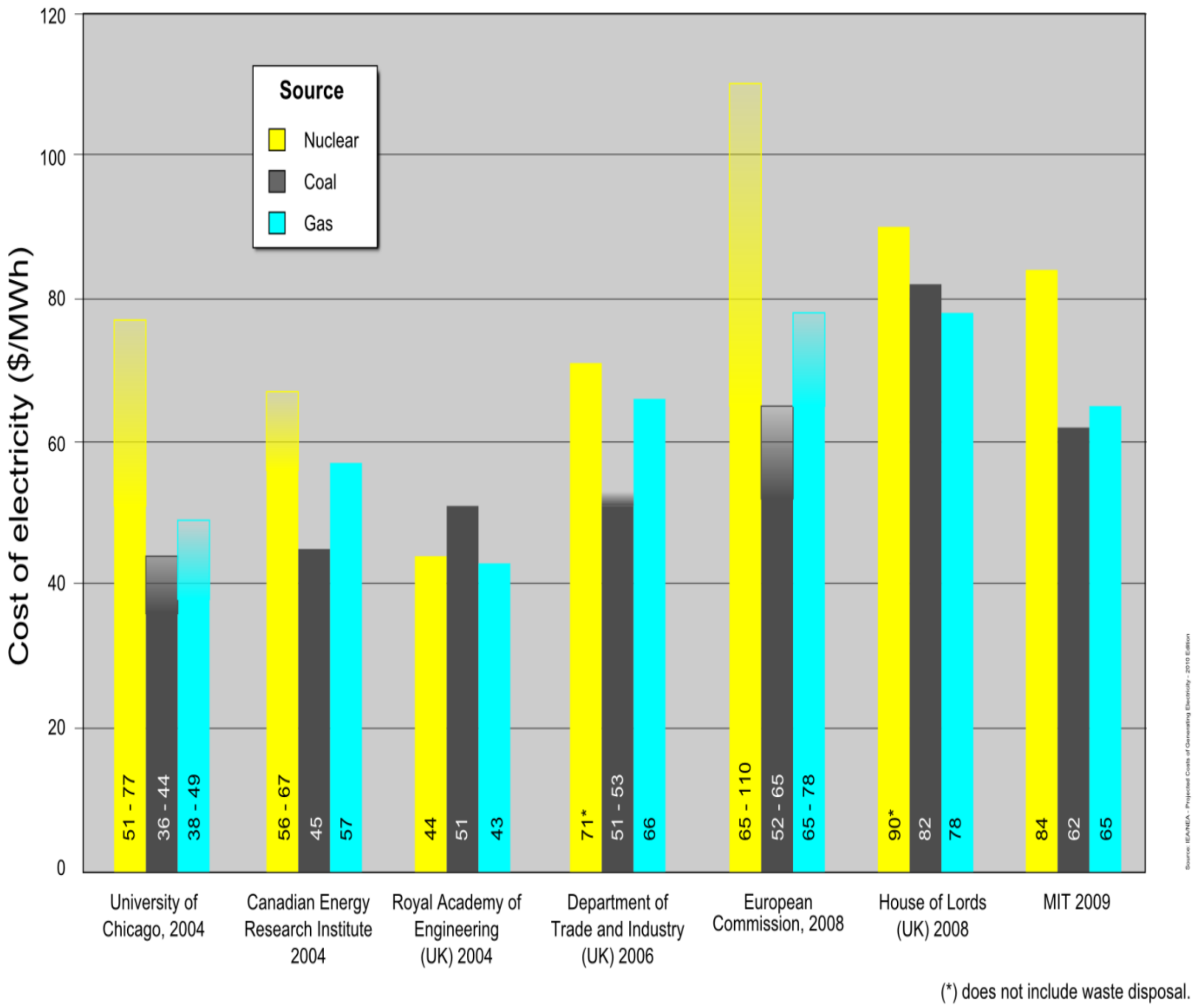

Fig.5Levelised costs of electricity according to different studies (2004-2009)

Source: Wikimedia Commons

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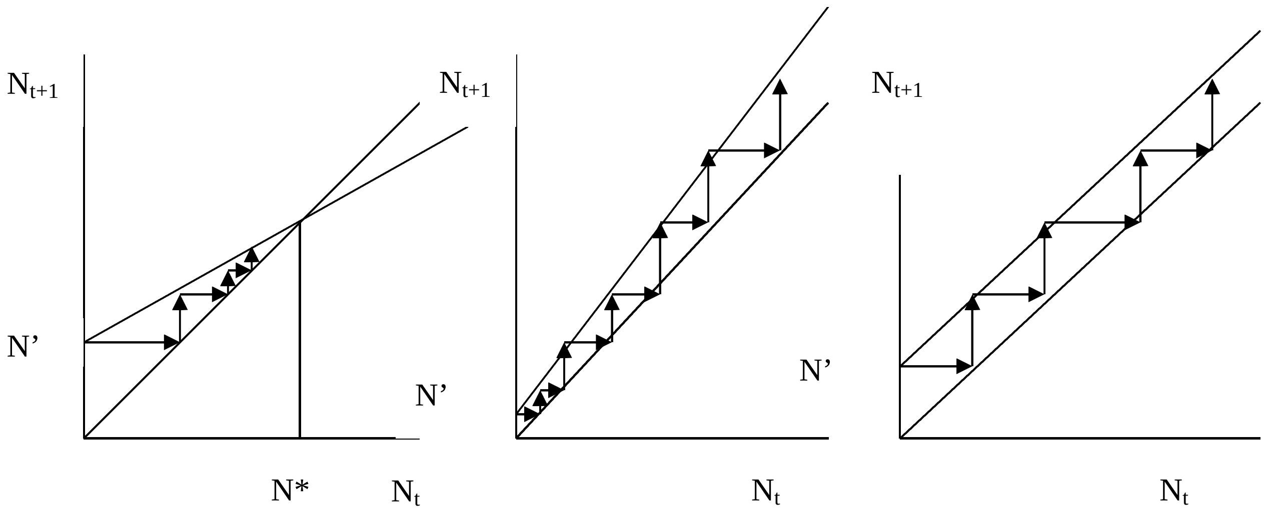

Subcritical case: *k<1* **Supercritical case: *k>1*** **Critical case: *k=1***

Fig.6 The dynamic regimes of a nuclear reactor

Source: elaboration of the author

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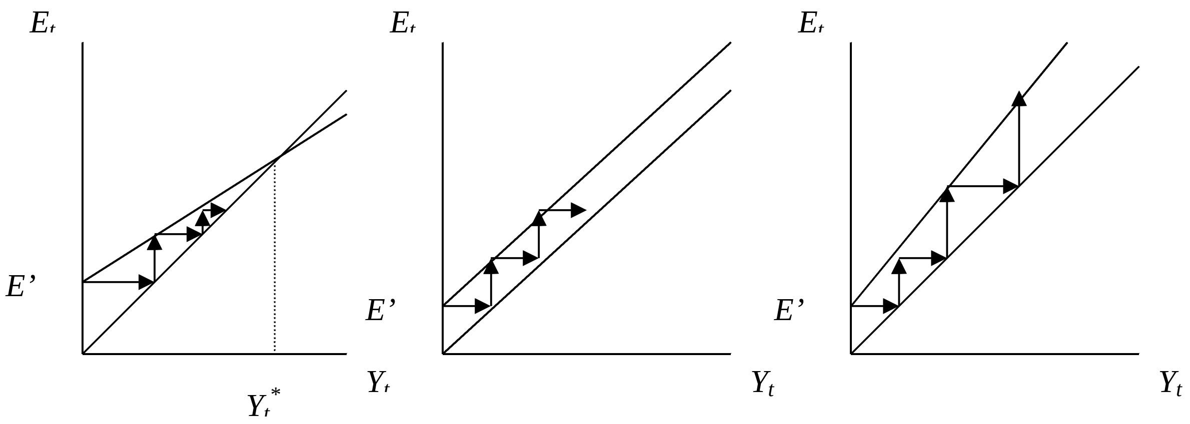

Subcritical case: the Kahn-Keynes multiplier

Critical case: the warranted rate of growth

Supercritical case: the upward knife edge

Fig.7 The dynamic regimes of a monetary economy

Source: elaboration of the author

Financialisation, Economy, Society and Sustainable Development (FESSUD) is a 10 million euro project largely funded by a near 8 million euro grant from the European Commission under Framework Programme 7 (contract number : 266800). The University of Leeds is the lead co-ordinator for the research project with a budget of over 2 million euros.

THE ABSTRACT OF THE PROJECT IS:

The research programme will integrate diverse levels, methods and disciplinary traditions with the aim of developing a comprehensive policy agenda for changing the role of the financial system to help achieve a future which is sustainable in environmental, social and economic terms. The programme involves an integrated and balanced consortium involving partners from 14 countries that has unsurpassed experience of deploying diverse perspectives both within economics and across disciplines inclusive of economics. The programme is distinctively pluralistic, and aims to forge alliances across the social sciences, so as to understand how finance can better serve economic, social and environmental needs. The central issues addressed are the ways in which the growth and performance of economies in the last 30 years have been dependent on the characteristics of the processes of financialisation; how has financialisation impacted on the achievement of specific economic, social, and environmental objectives?; the nature of the relationship between financialisation and the sustainability of the financial system, economic development and the environment?; the lessons to be drawn from the crisis about the nature and impacts of financialisation? ; what are the requisites of a financial system able to support a process of sustainable development, broadly conceived?'

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6	Poznan University of Economics	Poland
7	Tallin University of Technology	Estonia
8	Berlin School of Economics and Law	Germany
9	Centre for Social Studies, University of Coimbra	Portugal
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