

Radioactivity as sustainable source of energy : an oxymoron or a nature-inspired concept of resources management ?

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ABSTRACT

Evidence is growing that mankind must learn from nature , a self-sufficient and self-organized system that adopts all the opportunities to develop life and ingeniously makes the most of whatever energy source . Attempting to satisfy the requirements of our energy-consuming world , we cannot afford to disregard any available source of energy , mainly those characterized by zero-CO₂ emissions.

In this context an alternative scenario could be opened by the use of the nuclear radiations emitted from naturally occurring or artificially produced radionuclides . Abandoned mines of U, Th and Rare Earths , as well as storage areas of artificially produced isotopes all over the globe are available and affordable sources of radiations that can be converted in electrical power .

The transition from laboratory-scale nuclear batteries to large-area converting modules would allow to safely re-use a big amount of already existing radionuclides , converting a trouble into a resource .

INTRODUCTION

The first alarm about the criticalities that could arise out of an uncontrolled development of technology has been given by the Club of Rome , that in 1972 published the famous Report “ The Limits to Growth” [1].This fundamental study started to question the paradigm that the humanity had undefined available resources and could therefore perturb the ecological equilibrium without consequences .

The industrial era has been indeed characterized by an antagonism between environment and technology , this last designing and producing artificial objects and anthropomorphic systems with no analogs in nature , disrupting any balance between bio-sphere and techno-sphere .

We are now well aware of the fact that the limited supply of non- renewable energy sources cannot meet future needs . Moreover, the fossil fuels are not only “ non-renewable” , but , what is worse, are the major responsible of the abnormal climate changes, closely correlated to a CO₂ emission unparalleled over the past .

To respond to the sustainability challenges of the XXI century , the right approach to manage our world is not only the control of the impact exerted by the civilization on the natural resources, but rather the change of strategies to restore a nature-like self-consistent cycle of energy/ matter inter-change .

THE STATE of THE ART

Today's a lot of scientific work is going towards the modeling of man-made activities on nature-like technologies , and the inter play between the bio-world and the techno-world is opening new possibilities to reproduce systems and processes inspired by nature . Millions of years of evolution allowed nature to find the best solutions for a series of problems , such as the energy requirements of the biosphere . For the vegetable kingdom the solution was the photosynthesis process that convert the solar energy into energy for metabolic reactions .

In the search of innovative energy sources scientists tried to replicate such a process by assembling photovoltaic cells based on semiconductors . In particular the dye-sensitized solar cells proposed by Gratzel in 1991 [2] mimic the methods adopted by nature that uses complex bio-organic structures for light absorption and energy production . In the "Gratzel -like" devices the role of chlorophyll to transform photons into chemical energy is played by artificial dyes that, coupled with semiconducting materials , generate electrical power .

However the opportunity to convert sunlight into available energy, either metabolic or electrical, is offered only to systems exposed to the sun radiation , whereas we know that there is life also in regions isolated from the photo-sphere . Under such conditions life evolved developing alternative mechanisms for harvesting energy from other natural resources [3] . As disclosed by paleo-biological investigations , one of the other way followed from million years by biosystems for life flourishing in absence of solar light was to exploit the natural radioactivity [4 ,5] .

When radioactivity come into play, a generalized anxiety is generated , because people connect such physical phenomenon to the big catastrophes that occurred in the recent years (Chernobyl, Fukushima) . But radioactive decays are physical processes naturally occurring "on" and "around " the Earth . Mankind coexisted *ab initio* with radiations

emitted from terrestrial rocks and landed meteorites, as well as with cosmic rays raining down on the Earth.

The advent of the nuclear era and the related escalation of civil and military applications has led to a continuous production of a series of artificial radioisotopes, either obtained as by-products of fission reactions or purposely generated for specific applications, as diagnostics and medical therapies [6].

In each case the safe disposal of such radioisotopes, that can remain radioactive up to tens of thousands years, is a problematic task and the produced nuclear waste is an additive source of environmental radioactivity. From the point of view of safety the nuclear decays cause endless troubles but, from a different perspective, radioactivity can be viewed as an alternative source of power.

The idea to fabricate a nuclear battery is not new, the concept was firstly proposed by H.G.W. Moseley, who in 1913 fabricated and tested a device exploiting the energy released in the α -decay of Radium [7]. Further research work demonstrated that nuclear batteries could generate electricity by converting highly energetic α or β particles and γ radiations emitted from a variety of radioactive isotopes.

The generation of electricity from radioactivity can be obtained by means of thermal and non-thermal conversion mechanisms. In Fig 1 are schematically represented the main methods used for such conversion

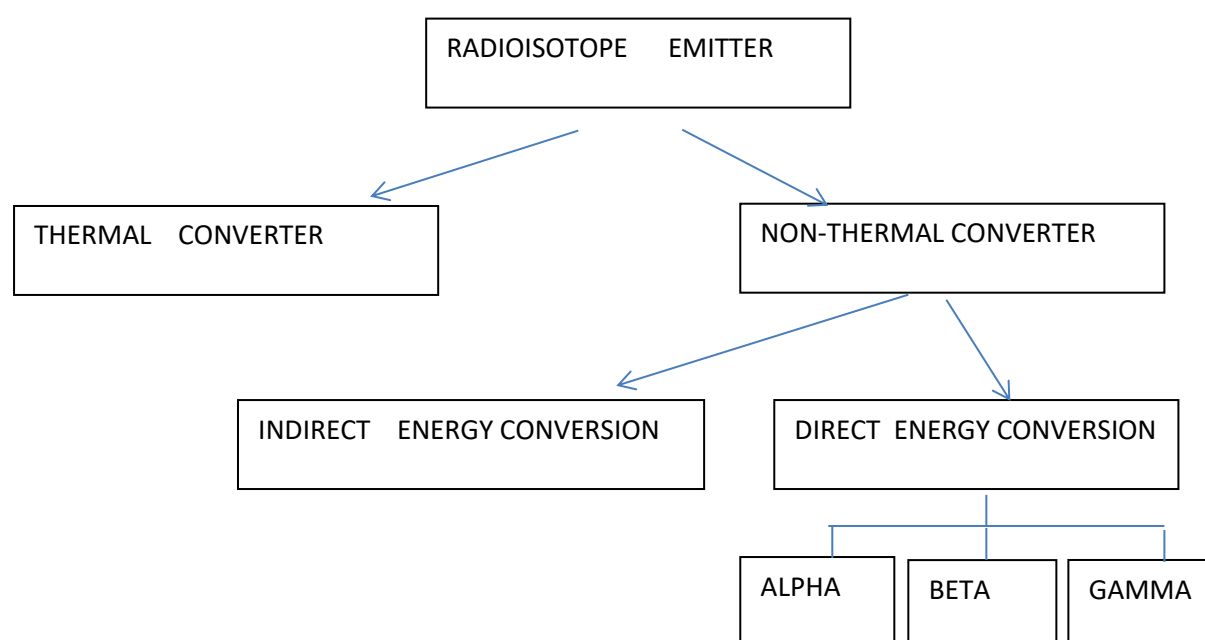


Fig 1 Classification of the main mechanism for conversion of radioactivity in electricity

A complete analysis of all the possible radiation sources can be found in [8]. This article takes into account not only the α , β and γ nuclear decays, but also the emissions of neutrons and fission fragments, and reports on the feasibility to fabricate nuclear batteries able to produce electricity on the basis of the various conversion mechanisms.

A β -voltaic solid-state device that produced electricity from the β -induced ionization of intrinsic semiconductors was patented in 1953 [9]. In such battery direct energy conversion was achieved using a diode configuration for the converter, with the radioactive source closely contacting the p-n junction (Fig 2).

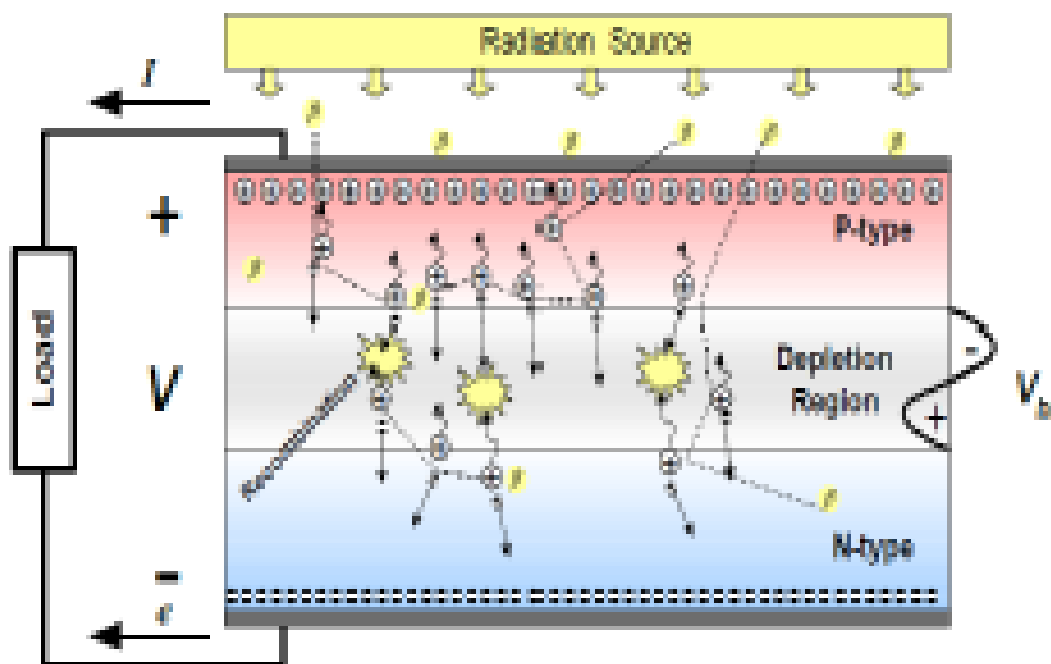


Fig.2 Scheme of the processes occurring in a semiconductor exposed to β -radiations and of the electrical circuit [From S.Kumar .arXiv 17 November 2015]

From the '70s to late '80s , β -voltaic cells based on the use of long lived radionuclides (mainly ^{147}Pm and ^{238}Pu) have been widely used to power pacemakers [10]. In the implanted patients such devices showed an extraordinary reliability combined with proper functionality and lack of safety risks . The current replacement of the nuclear cardiac devices with Li-powdered batteries has being motivated by other concerns , related more to security than to safety [11] .

The technology of batteries based on α -particles emitted from radioactive nuclides was developed in 1954 [12] . Wide band-gap and radiation-tolerant semiconductors are needed to convert the α -decay into electrical current , but the energy output of α -voltaic device is a factor ≈ 100 greater than that of a similar β -voltaic power source (assuming the same conversion efficiency) .

The plot of specific energy density (J/Kg) against specific power density (W/Kg) (Fig.3) shows that not only the α -voltaics , but also other nuclear batteries based on the direct conversion mechanism offer energy densities higher than any other power source [13,14] .

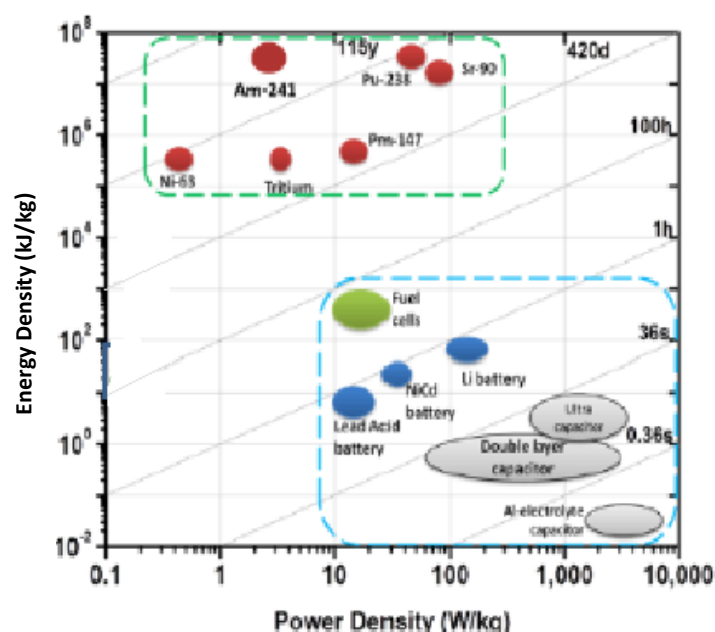


Fig. 3 Ragone plot comparing the performances of various batteries : capacitors (grey) chemical cells (blue), fuel cells (green) , nuclear batteries (red) . The lines indicate the discharge time for each technology [adapted from Ref. 14] .

However, the nuclear batteries with long shelf-life suffer from some intrinsic limitations, such as low specific power density, efficiency typically <10% and radiation damaging of the converter material [15]. Moreover there are obstacles to decrease the cell size.

The effective miniaturization of nuclear devices is presently a virtually unattainable objective, mostly when the highly penetrating γ -rays are the radioactive source and a proper shielding is needed. The failing to down-scale batteries size is a critical constraint that virtually hampers the integration in the ever-smaller and extremely compact electronic devices used in several technological fields. The whole of shortcomings is nowadays restricting the usage of nuclear batteries only to some niche applications. In particular such energy sources are employed in sensors or communication devices/ nodes located in remote or harsh environments, which are required to last the lifetime of the infrastructures [16-17].

Nevertheless, the advantages offered by the long lifetime is still pushing researchers to improve the performance of the radiation-based solid-state systems, making them appropriate for a wider range of end-uses. Recent studies demonstrated that a non-conventional design of the converter, together with the choice of a proper semiconducting material and the control of the surface nanostructure, can enhance the electrical power output. The specific energy of a β -battery based on diamond in a Schottky diode configuration can indeed reach values an order of magnitude higher than those of a conventional chemical cell [18]. Up to now several converter configurations have been tested, producing devices with innovative quasi-vertical, vertical and also “corner” architectures.

Even if there are no doubts that optimization of the cell design and new fabrication routes will in future improve the performances of such batteries, the combination of downsizing constraints, low conversion efficiency and limited power density is hindering a large scale commercialization of nuclear batteries for integration in tiny electronic devices.

But the above mentioned drawbacks are really limiting the possibility to use nuclear radiations as an alternative energy source?

PERSPECTIVES and CHALLENGES

Thinking to the mines of natural radioactive elements as well as to the storage facilities of spent nuclear fuel and of radioactive waste, it is clear that such premises could be regarded as rather “endless” sources of an energy that wait only to be properly captured. If the objective is that of centralized utility-scale installations and not of mobile units, the inability to downsize the batteries is no more a concern. Moreover, one would no longer speak of a truly “battery”, i.e. of a complete system that supplies electrical power by conversion of energy from an internal radioactive source, but merely of the transducer, i.e. the semiconducting component that acts as power generator.

Large plants could be fabricated inside abandoned mines of U, Th and rare earths, or storage areas of artificially produced isotopes, available and affordable sources of radiation all over the globe.

When huge deposits of natural or artificial long-living isotopes are put into play and a unexhausted supply of high-energy radiation is guaranteed, all the drawbacks experienced in harvesting power by means of nuclear batteries are expected to fade.

In a centralized installation the issue of reaching high power levels can be easily tackled by connecting a number of converters in large modules, overcoming in such a way the low efficiency of the direct or un-direct mechanisms involved in the conversion of radiations into electrical power.

As regards the radioactive sites, there is an ever growing public concern about them, however not all the radiation sources are looked at with the same attention. Storage sites of radioactive waste produced in nuclear plants face effective protest by citizens and the risk perception influences negatively the public acceptance, even if such installations are object of severe regulatory issues.

Conversely, little or no attention is paid to the mining sites of radioactive minerals and to the issues of safety, environmental effects and also security related to such radioactive premises. In this context one must figure out not only the operating mines, but rather the disused ones. Around the world there are indeed a lot of old U, Th and rare earth mining areas that, after the closing of exploitation, have been abandoned by the companies without any on-site recovery (Fig.4).



Fig.4 . View of a typical abandoned U mine .

The abandoned sites and their surroundings could represent a hazard for the populations exposed to high levels of ionizing radiations . As reported in. [19] , in many cases the exposure exceeds the reference values established for annual effective dose limit by the USCEA [20] .

The mitigation of the effects produced by high-level radiations needs a deep rehabilitation of the legacy mines . However such topic does not affect the public perception , therefore the protection against radiations in former mines is not seen as a pressing objective . In this view the putting in place of recovery strategies is very unlikely, unless outstanding economic interests were coming into play .

The planning of a centralized battery bank based on multiple energy converters should provide the positive side-effect to guarantee the security of the sites . In this context the threats connected to the disposal of the large amount of nuclear waste and of highly radioactive soils would be turned into an opportunity .

However , just speculating about the use of radioactive sites for power harvesting causes a widespread anxiety among general public . The perceiving of radioactivity as a frightening hazard , no ifs and buts , could represent a stumbling obstacle able to stop not only any initiative , but also any feasibility study .

What is not perceived is that precautionary approaches to the use of radiations, even of high level ones , are currently feasible . In power installations , how done in damaged reactors or in nuclear waste warehouse , the running of the building and operational phases would be remotely controlled by mechatronic systems and unmanned platforms

The legislative and regulatory issues with which to comply are the results of old studies on the interferences of the radiations with the physiology of living species and on the adverse effects induced in cellular components . These studies led in the 1950s

to establish the linear no-threshold (LNT) model adopted since then by international advisory bodies. The LNT paradigm assumes that health risks occur independently from the energy of radiations, with alterations of DNA functions and genetic code and increase of cancers. However, the contradictory concept of radiation hormesis, i.e. of the benefits for health of low-dose radiations [21] is now well demonstrated [22-24].

Moreover in recent years it has been discovered that for some organisms growing in radioactive environment not only cell survival is ensured, but there is evidence that the organisms utilize radioactivity as a source of metabolic energy. Such unexpected behavior was preliminary noted at the end of 50's in fungal colonies grown in Nevada nuclear test sites [25]. More recently it was discovered a flourishing of single-cell fungi in the highly radioactive areas surrounding the damaged Chernobyl Atomic Energy Station or in the cooling water of still operating nuclear reactors [26].

The studies on the species dominant in soils contaminated by naturally occurring or anthropogenically originating radionuclides, as well as in the high-radiation environment (i.e. Antarctica highlands) enabled to disclose that in all cases such species were rich in melanins [25,26]. The broad term "melanins" indicates a class of naturally occurring conjugated polymers, based on $C_{18}H_{10}N_2O_4$ molecular sub-units.

Whereas at the beginning of 2000's was well known the capability of melanins to absorb a wide range of the electromagnetic spectrum, at that time there were only hypothesis about the way followed by melanins to transform dangerous α , β and γ radiations in energy for physiological processes. Evidence proving the radiation-induced increase of metabolic activity was achieved from experiments carried out on *C. neoformans* cells exposed to high radiation levels. The laboratory studies highlighted modifications of the melanin electronic structure in irradiated cells and allowed to quantify the melanin-mediated electron transfer rates, that were found up to 4-times increased when compared with those of unexposed cells [27,28].

Afterthat other studies confirmed the role of melanins in the growth of melanized fungi exposed to ionizing radiations [29-31].

Attempts to understand the way radioactivity is transformed by melanins in energy available for metabolic processes evidenced similarities with the mechanisms adopted by chlorophyll in turning energy from radiations into bio-energy. In both cases what come into play is the electronic structure of the chemical species, but, whereas chlorophyll generates chemical energy from non-ionizing radiations through the *photo-synthesis*

process, melanins carry out *radio-synthesis* processes, converting the ionizing high energy portion of the electromagnetic spectrum as well as radiations from nuclear decays. In living organisms melanins exploit charge transport following multi-step electron transfer pathways. This semiconducting behavior accounts for the consistent presence of melanins in some specific locations of the human body, as retina, inner ear, midbrain (*substantia nigra*) where charge transfer phenomena take place.

The electronic properties of eumelanin, the most interesting component of the melanin family, had been outlined in 1972 by J.E. McGinness [32] who also tested the material as an amorphous semiconductor threshold switch [33]. The capability of the eumelanin to parallel, or also to go beyond the performances of inorganic amorphous semiconductors, led in recent years to investigate the viability of a melanin-based bio-electronics [34]. In Fig.5 is shown the molecular structure of the eumelanin oligomer.

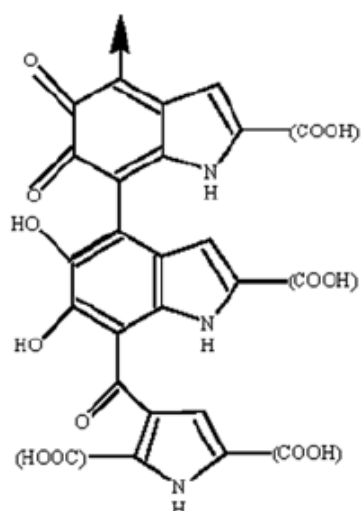


Fig. 5 Structure of the eumelanin oligomer

Even if it is now well established that the ability of some organisms, as the radiotrophic fungi, to withstand high doses of ionizing radiation is due to their richness in melanins, details of the mechanism implemented by melanins to assure cell survival safeguarding DNA are not yet been clarified [31, 35]. Among the hypothesis proposed at a speculation level to explain the radiation resistance of melanized organisms, the most accredited is that melanins succeed in quenching the cytotoxic free radicals produced by radioactivity [35-37]. In this context studies on melanins are been

mainly performed by biologists, who are still trying to reshape the conventional schemes about electron transfer in metabolic pathways [30, 35].

The advances in the field of organic/ bio-inorganic electronics and optoelectronics yielded in recent years a large number of publications dealing with melanins, and guidelines to understand charge transport features of such organic semiconductors are now provided [38]. However it is to be noted that, whereas a lot of applications are being proposed for bioelectronics and biosensing [39-42], the issue of energy harvesting by melanin-based devices is overlooked by the scientific community. This is likely due to the output of several studies that evidenced an intrinsic low conductivity of the material, poor performances in converting light into electricity and a scarce stability of melanins under long-term illumination.

However, such drawbacks regard the efficiency of light conversion, in which melanin is certainly not competitive with inorganic and also some organic semiconductors. If ionizing radiations are taken into account as energy source, the approach must be completely reversed. It is indeed well known that ionizing radiations have a strong detrimental impact on inorganic semiconductors, limiting therefore their use in highly radioactive environment. The low resistance to radiations of conventional semiconductors is precisely one of the arguments put forward against the development of nuclear batteries. On the contrary, due to its properties, melanins could act as a successful active material in converter devices for electrical power production.

The consequence of the papers published in 2007 - 2008 [27-29] was a focus pulled on melanins/ radioactivity systems for production of metabolically useful energy. Many reports and commentaries disseminated information about the melanin's performances in capturing and living off radiations, but the interest was exclusively towards the increased growth of some living organisms and the transformation of radiations into "food" or biofuel. Some exciting ideas have been proposed, such as to use radiotrophic -fungi to destroy radiations and radioactive particles, or to feed astronauts during future long voyages in space using galactic cosmic rays to grow eatable organisms. The scouring of the biomedical literature allows one to find many studies and commentaries that discuss the role of melanin in mitigating the effects of radiation, radioisotopes and fallout on living species. Melanin-rich fungi have been tested as radioprotective food [43,44] and ESA recently funded a project to evaluate

melanin-based materials for the human protection during space flight missions [45] .

Overall ,in the last decade the traditional picture of melanin as the pigment absorbing harmful components of the solar spectrum has been widely broadened., to include the unexpected features of radioprotection . What are missing , conversely , are studies/speculations about the possibility to capitalize on the opportunities that melanins can offer for electrical power production from radioactive sources . Certainly not an easy task to be pursued , but a bounded problem with a realistic development timeline. Considering that mankind is now addressing much more complex and challenging task , as the colonization of Mars , the design of plants to convert radiations into electrical power would be a children's game .

CONCLUDING REMARKS

Other are the issues that can really impede to attain the objective to produce energy ,with zero-CO₂-emissions , from already existing radioactive sites , converting therefore a trouble in a resource . The first one is a somewhat compartmentalization of researches. It is to be noted that each topic briefly outlined in this paper , namely radioactivity, nuclear batteries and melanins , has been - and still is - the object of deep investigations carried out in the frame of highly specialized and sectorial scientific /technological areas .

As an example , the idea of energy harvesting from radioactivity , launched inside the restricted community of researchers working in nuclear technologies, did not trigger up to now the attention of people addressing the topic to rebalance energetic cycles and processes for a sustainable development .

As a general rule the management of the fast changes of today's world and the tackling of society's grand challenges must pass through the strategic priority to create a fertile ground for really multidisciplinary collaborations covering the whole spectrum of technologies .

The second big issue is the negative perception and subsequent low acceptance of radioactivity , even of the low-level one , by the general public . It is to be noted that the concern about radioactivity in our society is greater than the actual health hazard . This depends mainly on the lack of a correct scientific information necessary to overcome

the generalized fear created by the catastrophic events of the last decades . The matter to earn the public's trust should be addressed by launching initiatives and promoting effective information campaigns about risk assessment and related regulatory issues . Arguing about the technical capabilities to safely manage either natural radioactive sites or nuclear waste deposits and debating of salient benefits could help in off-setting irrational concerns .

At this stage of global systems development , when “what to do” is a challenge of the outmost importance, the issues of non-segmental technologies and of a new social consciousness are strategic priorities . As indicated in the more recent report of the Club of Rome [46] , collective actions must be planned through the cooperation of experts on technologies, governments and all sectors of society.

If the goal is to overcome the systemic crisis of civilization , mankind must learn lessons from nature , that adjusts its methodologies to tackle any adverse event , reaches its goal limiting the use of resources , maximizes the processes efficiency and transforms catastrophes in opportunities for life .

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