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From hydrogen economy to hydrogen civilization

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Abstract

For the first time ever, the main aspects of a move by humankind into the era of an ecologically clean hydrogen energy civilization are being considered. It has been shown that energy and environmental problems can be averted by changing our energy carrier from fossil fuels to the environmentally clean energy carrier, hydrogen. The biospheric and noospheric consequences of this transition have been analyzed. The steps to be taken for the move to such a future hydrogen civilization have been discussed.

Keywords: Hydrogen energy; Hydrogen economy; Hydrogen civilization

1. Introduction

According to Vernadsky's studies [1–4], a biosphere is an "organized, specific crust envelope of the Earth associated (mated) with life". So, the biosphere is bounded first and foremost by the region where life exists, and the living matter is a driving force of the biosphere.

As is known, our biosphere functions as follows: The Earth as a heavenly body exchanges energy and matter with the other heavenly bodies in space. The matter reaches Earth as meteorites, space dust, microparticles, elementary particles of solar and space wind, etc. The Earth derives energy first of all in the form of solar radiation. As a comprehensive consideration, one should also consider the energy derived from other space objects in the form of electromagnetic radiation, microparticles energy, etc. Solar radiation certainly is the foremost factor for the existence and functioning of the biosphere. In what follows, we shall consider just this energy source.

The entire solar energy that the Earth derives can be divided roughly into two parts. The first part is the Earth's thermal radiation. For the most part, this is longwave electromagnetic radiation. It passes partially through the Earth's atmospheric shell and proceeds into outer space. A certain part of this Earth-based radiation is blocked by the atmospheric shell, speaking figuratively, or by an atmospheric "blanket". The Earth-space energy exchange results in some steady state, and our planet becomes warmer (in comparison with the space temperature mode) and supports the life forms on it. The other part of the solar radiation the Earth derives is converted by the biosphere (for the most part, through the work of plant life) into storable forms of chemical energy.

Vernadsky thoroughly developed every biogeochemical aspect of biosphere's functioning. In doing so, he distinguished and analyzed in detail the cycles of circulation of chemical elements and living matter components. He showed further that these cycles, speaking in a modern scientific language, are stationary and self-maintaining. They are not closed, and over the course of geological times, a part of the matter and energy leaves them, being stored in the crust and forming such deposits like coal, oil, etc.

In the context of this work, the carbon cycle is of special interest in which carbon dioxide (CO_2) is of utmost significance. It is emitted into the Earth's atmosphere through the vital activity of animal life, and absorbed and processed by the plant life (with the release of oxygen into the atmosphere). It is involved in the formation of minerals on land and in the aquatic environment, etc.

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Vernadsky, the founder of the noospheric studies, perceived both the geological vastness of human activity, and the unpredictability of its consequences. In Refs. [1–3] he wrote, “We observe a more and more dramatic influence of a human intellection and collective mind on geochemical processes”; “Of special interest and a characteristic fact in the history of carbon, is the fact that carbon dioxide increases as the history of civilization evolves”; “In this way a civilized person disrupts the equilibrium established on the Earth”. Vernadsky emotionally stressed, “Here human beings behave not like *Homo sapiens* but like *Homo sapiens faber*”. He exclaimed, “Where will this new geological process stop? And will it stop or not?”

Slightly more than half a century since the great thinker’s death, it has been established that human activity in this direction has approached an unreasonable scale. Speaking with a sad irony, it is possible to say that we are approaching (or may have already entered) a civilization of *Homo desipiens faber.*

2. Greenhouse effect and global environmental problems

When considering the ecological future of the Earth as a whole and of its various regions, the deciding factor of the formation of the biosphere, including the ecological system as a part of it, is first and foremost the kind of energy carrier that is being mainly used by humankind. The main energy carrier used today is the fossil carbon fuels, namely, coal, oil, natural gas and products of their processing.

On the global scale, burning of hydrocarbon fuels causes an increase in the carbon dioxide content in the atmosphere. According to the German physical society [5], the atmospheric CO_2 content for 100 years, between 1850 and 1950, increased by $\sim 15\%$, and then from 1950 to 1988 it experienced an annual rise of $\sim 0.3–0.5\%$. In 1988, the atmospheric CO_2 content was as much as 359 ppmv, and in 2000, it was in excess of 390 ppmv.

The CO_2 content increase (as well as NO_2, CH_4 and some other gases) in the atmosphere brings the greenhouse effect into existence. It results from the carbon dioxide content in the atmosphere, which is mainly responsible for controlling the part of the Earth’s thermal radiation which escapes into outer space. This part decreases with the CO_2 content increase in the atmosphere, and consequently, a shift in the dynamic equilibrium towards a general warming of the Earth takes place [5–10].

In the last few decades, the greenhouse effect [7,8] and its possible consequences have been studied all over the world by a number of specialized research institutions and analyzed by outstanding scientists. Predictions are unfavorable. A general average warming of 1–2 K, expected in the successive decades, will cause highly disastrous planetary effects, namely icecap melting in the Arctic and Antarctic Regions, a sharp climate change, especially with disastrous effects, for some individual regions, such as droughts, floods, disruptions in agricultural activity, etc. All of these aspects are widely covered in specialized and vastly circulated periodicals, perceived not only by scientists, but also by the general public. The problem is certainly within the scope of international organizations, such as the UN and its specialized agencies. International conferences and negotiations [8–10] are held. For “greens” and their parties, the greenhouse effect and an expected environmental disaster have become important attributes of their movements. It has been found that certain countries are the leading contributors to the oncoming disaster. By their percentage in the world-wide volume of harmful effluents, the following countries are major contributors: the USA-24%, China-14% and Russia-6%.

In 1997, in Kyoto, Japan, the leaders of the main countries signed an agreement by which they were to take steps to reduce harmful effluents into the atmosphere. It was supposed that in 3 year’s time, the non-feasance would imply punitive measures.

During November 22–23, 2000, in the Hague, the Netherlands, there was again a conference organized by UN and the World Health Organization. The latter was concerned that 6% of all deaths were the result of environmental pollution. The Conference efforts failed. It can even be said that it turned out to be a complete fiasco. This was a natural result due to a diversity of global stimuli: political, economical, technical, scientific, etc., affecting each of the countries involved. Let us consider the reasons for the failure. The main reason, undoubtedly, was that a very complicated and complex world-wide environmental problem was conceived to be solved by the most plain and short-term method of attack, namely, by a simple undertaking of some obligations by the countries, in the form of quotas, to reduce harmful emission into the atmosphere.

One could illustrate the incongruity of such an approach through an example. According to the agreement signed in Kyoto, the USA was to reduce harmful effluents by 7%. But everybody knows that the USA has a growing economy. Rather than reducing the effluents, this country increased them. It is clear that any administration of the USA will not risk depriving the nation of its economic growth, no matter what commitments it has sanctioned. They will employ certain sanctions, but they will never run the risk of stifling their economy. All countries of the “golden billion” will undoubtedly behave in a similar manner. And so will poor countries especially as they can ill afford to freeze the energy consumption growth.

To put it precisely, any solution to solve the greenhouse effect and to avert a world environmental disaster by restricting energy consumption will have no prospects of success. It is pertinent to note that Vernadsky stressed that any call for a return to a primitive life (such calls, both in a direct and veiled or mild form, were always put forward) is not well grounded and cannot be realized in practice. Such an idea, speaking figuratively, is a “still-born” idea.

But a positive (not premature, not before its time, not risky) way out for the humankind still exists, and it has been systematically worked out for a quarter of a century. We can say that it has already emerged from its latent position, and it is high time to exert the effort to see that most of humankind adopt this concept.

3. Hydrogen economy: conception and present status

A large-scale concept of ecologically clean hydrogen energy system came up in the mid-1970s as a natural response of a conscientious part of the world scientific community to the impending environmental disaster, the dwindling natural resources of hydrocarbon fuels (initially oil and gas), and the world-wide energy crisis at that time [11–17]. Utilizing hydrogen does not produce any harmful effluents, nor does it produce CO_2. It is evident that using hydrogen as an energy carrier automatically solves, in principle, the global problem of the greenhouse effect, as well as the regional environmental problems.

In the context of the development of this ideal, the International Association for Hydrogen Energy (IAHE) was established with its headquarters at the Clean Energy Research Institute, University of Miami, Coral Gables, Florida, USA. The IAHE began publishing the *International Journal of Hydrogen Energy* and holding biennial World Hydrogen Energy Conferences [18].

By the mid-1980s, the hydrogen energy (HE) concept had been completely worked out and presented in detail, its scientometric analysis had been done, and its structure had been developed [19,20]. In short, it comprises (1) hydrogen production from water using non-renewable energy sources (coal, atomic energy, thermonuclear energy) and renewable energy sources (sun, hydro, wind, currents, tides, biomass, and so on), (2) hydrogen delivery transportation and storage, (3) hydrogen utilization in industry, transport (land, water and air) and home, and (4) problems of material reliability and systems safety. Scientific research on HE has taken place and is ongoing in more than 40 countries. Some countries have adopted national programs and/or initiated large projects on the HE development (e.g., Japan, Germany and USA). Since the world economy runs on energy, the term “hydrogen economy” [21,22] has received a wider usage.

Some of the major hydrogen energy programs are mentioned below:

- Japan: Their WE-NET Program is managed and financed by the Japanese Ministry of International Trade and Industry. In this program, Japan plans to spend $4 billion by 2020 to develop hydrogen know-how in order to move toward the HE system. In the future, they plan to form artificial islands in the equatorial parts of the Pacific Ocean, and using solar radiation, they plan to produce hydrogen by electrolysis from sea water.
- Germany: They have a program by which a solar-hydrogen energy mini-system is being devised close to Neurenburg. The Solar-Wasserstoff-Bayern has built a solar-hydrogen plant there, besides a hydrogen storage system, and hydrogen utilizing systems and appliances.
- Germany and Saudi Arabia: These two countries are cooperating in a joint program called Hysolar. Under this program, they have built a solar hydrogen production plant near Riyadh, Saudi Arabia, the world’s largest petroleum country. Eventually, Saudi Arabians expect to be the permanent exporters of energy in the form of solar hydrogen; and they are preparing themselves for it.
- Europe and Canada: The Euro-Quebec (a European and Canadian joint project) is another successful international program. They have been looking into applications of relatively inexpensive hydro power produced liquid hydrogen imported to Europe from Canada—applications such as city bus transportation and smelting of iron, as well as the development of an infrastructure for overseas transportation and storage of liquid hydrogen.
- Iceland: Icelandic Government, universities, transportation companies, fishing fleet operators, utilities, and multi-national car and petroleum companies have formed a consortium. They are working towards converting Iceland to a complete Hydrogen Economy by the year 2030.

By and large, the results of the hydrogen economy development within the span of 25 years are summed up in [18]. The results are impressive. Some companies have already begun to commercialize hydrogen technology, hydrogen know-how and hydrogen energy systems, e.g., automobiles running on hydrogen fuel, fuel cells, improved electrolyzers, hydrogen–nickel batteries, and so on. A stable hydrogen scientific community has been formed. They have begun to study the prospects of developing separate aspects of the hydrogen economy up to 2020, 2050, and even up to 2100 [23–36].

But, at the moment, the research being carried out covers either a region and/or certain technical aspects of the Hydrogen Economy. For example, there are studies which are pertinent to the USA, Brazil, Spain, Egypt, Iceland, etc. [37–41]. They are studying prognostic problems of the hydrogen energy system requirements for the future, electrical energy required for hydrogen production, and other similar questions. From an engineer’s viewpoint, such an approach is fully justified; this makes it possible to forecast and later on solve the important technical and economical problems of the Hydrogen Economy.

As a result of the above, one can see a future global planetary role for the Hydrogen Economy. This role will be very important, both in the whole planetary spatial scale, and in the historical and geological time scale. The very definition of the problem in such a way, specifying biosphere and noosphere problems to be scientifically worked out, is, as we see it, a very significant moment which has to be comprehended, analyzed and studied systematically by the world scientific community.

4. Transition to hydrogen civilization

When it was proposed, the Clausius' hypothesis of the Universe's "thermal death" was of great interest. This meant that in the future the temperatures everywhere in the Universe would be the same. In accordance with the second law of thermodynamics, entropy would reach its maximum, and the whole Universe would correspondingly reach a state of thermodynamic equilibrium or a "thermal death". Vernadsky's genius revealed itself in particular to the fact that being a planetary thinker and naturalist (but not a physicist), he had uniquely perceived that this hypothesis could not be applied to living matter (and hence to the biosphere as a whole). He underlined this thought many times in his works [1–3]. At present, Clausius' hypothesis is of interest only for the history of science and philosophy. On the contrary, Vernadsky's views on this question were fully within the realm of modern science.

In the last few decades, a new interdisciplinary science "synergetics" has been founded [42–44]. It describes the behavior of highly non-equilibrium systems (that is physical, chemical, technical, biological, economical, sociological, and so on) consisting of a large number of subsystems. These systems are in continuous energy and matter exchange with the outward world, and under certain conditions regular self-organizing processes are possible within them. A characteristic property of these systems is that, in their way of development, there may exist the so-called bifurcation points, wherein the possible system development routes may fork out. An important moment here is that at such a point the system is in an unstable state, and small random disturbances can lead to global impacts. Then the system could irreversibly progress in the direction of one of the possible routes, which may differ quite fundamentally from one another.

It is evident that the biosphere is in a highly non-equilibrium state, exchanging energy and matter with outer space. It consists of a large number of subsystems. Every day it becomes clearer that the future biospheric developments should be studied in the context of the systemical and synergetic approach. Such an approach must firstly be applied to the study of different scenarios of possible development in the biosphere in relation to the greenhouse effect and possible environmental disasters, and secondly, it must be applied to precautionary measures and their consequences. Then the following interrelated scenarios require urgent consideration.

Scenario 1: Consider the biosphere development for conditions when amounts of CO_2 and other harmful effluents continue to increase. What will be the impact on biosphere at different rates of effluent increase for different intervals (in 25, 50, 75, 100 and more years)? Such a global scenario should elaborate on the consequences for all biosphere biogeochemical cycles for all interacting biosphere subsystems, and for humankind and its habitat.

As yet, synergetics gives no mechanisms to evaluate possible ways for the development of non-equilibrium, self-organizing, highly complex systems, and to evaluate their ability to reach bifurcation points and beyond. But the very knowledge of the general laws of synergetics and the possibilities of the existence of bifurcation points provide fundamental ideas for investigations of this kind. Here, it is important to establish how much time humankind has before the biosphere and ecosystem enter into an irreversibly catastrophic phase of its development.

Scenario 2: The biosphere development when there are realized global and regional programs of a progressive, at first partial, and then complete replacement of hydrocarbon fuels by hydrogen at different rates of hydrogen energy introduction and for different time intervals (viz., 25, 50, 75, 100 and more years). There has been an initial and encouraging study [45] showing that the introduction of hydrogen would help in returning the biosphere to is pre-industrial state. Let us now highlight some a priori visible global peculiarities for the developments under this scenario.

As noted above, Hydrogen Economy development is largely based on the expansion of the use of renewable energy sources, namely, solar energy and its derivatives. This means that there will appear a new factor changing the existing conditions of thousands of years of stationary distribution of solar energy, which is immediately "used" by the Earth and given back to the outer space. So, with the use of hydrogen as an energy carrier, a decrease in the emissions of technogenic effluents into the atmosphere, and an increase in direct solar energy utilization will result in the change of the existing conditions on the Earth and the biosphere as global, highly non-equilibrium systems. Humankind must certainly calculate the consequences: if these factors are essential, how many other factors will be essential, and what will be the new stationary dynamic state of the biosphere, and how fast this state will come into being? Undoubtedly, the regional stationary states for all biogeochemical cycles, including the carbon cycle, will also undergo changes. What will these changes be?

It is evident from the above that the Hydrogen Economy entry into life will not only solve the world's environmental problems, but will also produce changes in the biosphere and its functioning over the historical and geological scales of time. Without exaggeration, one can say that along with this, humankind will enter a new era: Hydrogen Civilization.

5. Perceived noosphere self-organization: decisive condition of transition to hydrogen civilization

The noosphere is a special stage of the biosphere development when a dominant driving force of its self-development is science, with a human intellectual activity as a general planetary phenomenon. A transition to the Hydrogen Civilization era will inevitably occur, as a result of a natural biogeological phenomenon. This transition will be realized by the noosphere self-organization conditioned by the human intellectual activity. A transition of such a scope and significance cannot be realized over a short period. It will be realized by humankind in the historical period of its rational activity. Slow-downs and back-steps are quite possible here. It is expected that this historical transition will comprise the following stages of development, which may take place successively and/or concurrently.

Stage 1: The stage of a systemical study of these changes in the functioning of the biosphere, its sub-systems and, in particular, the Earth's ecosystem, which will be induced by humankind are as a result of the changeover to the new energy carrier—hydrogen. This stage is noospheric indeed, and an important segment of the world scientific community will take part in it. The germ of such a community is already in existence in the form of the world hydrogen movement [18–20] and the environmental community of analysts, who are studying the greenhouse effect, its disastrous environmental, economical, political and other impacts. The integration of efforts by these scientific communities will be an task of urgency at the preliminary stages of the change-over to Hydrogen Economy. Scientific results available at this stage have to provide humankind with real, highly plausible, accurate, comparative and predictive estimates of biospheric, environmental and other consequences of a wider use of energy carriers in question, i.e., hydrocarbon fuels and hydrogen.

Stage 2: The stage of formation of a new environmental and noospheric consciousness of the general public of all the countries: This new consciousness (intellection) cannot be based, figuratively speaking, on the idea of "moving ahead to the primitive living" by putting vetoes on energy consumption. This new consciousness will be based on scientific, and highly reliable predictions about the manner and rates of humankind's change-over to the environmentally clean energy carrier—hydrogen. It is important that the present world hydrogen scientific community permanently pay great attention to this "unscientific" but absolutely necessary activity, without which a transition to Hydrogen Civilization is impossible. The role of the general public of highly industrialized countries is especially important, because most of the world's science is concentrated in these countries, and at the same time these countries pollute the environment most. It is obvious that humankind has a right to expect, from these countries, the largest intellectual and financial contribution to the transition to the environmentally compatible Hydrogen Civilization. The general public in both the countries of transforming economies and in the developing countries has to be involved in this process in a full measure.

Stage 3: The stage of an official consideration of scientific predictions of how humankind should develop its international and regional organizations, such as the UN and its agencies (UNESCO, UNIDO and others), the World Health Organization (WHO), the European Council, the Council of the Inter-Parliamentary Assembly of the Countries, the CIS members and other similar organizations. A world-wide public discussion of the results of this consideration should follow. International and regional organizations should adopt the framework laws and recommendations for the governments and parliaments of all the countries, which would outline the scientifically founded and economically acceptable ways and mechanisms for the transition to Hydrogen Civilization. The work at this stage will lead to a more effective international cooperation.

Stage 4: The stage of consideration by the parliaments of the framework laws and recommendations suggested by the international and regional organizations as to the transition to Hydrogen Civilization regarding specific conditions of individual countries: The living standards of each country and its economic state, scientific potential, environment and so on should all be considered. The designing and adoption of laws should follow for the regulation of financing and the establishment of comprehensively organized national enterprises, which would encourage the use of hydrogen, investment of private capital and the establishment of a competitive market for hydrogen energy.

Stage 5: The stage (historically this is a prolonged stage) of a scientifically, legislatively and economically ensured transition to Hydrogen Civilization. This stage may not result and should not be so conceived as some simultaneous changeover to the Hydrogen Civilization. Being historically prolonged, this stage may spread in a highly uneven, and fragmental manner in geographical space, by individual branches of engineering, technology, production, and so on. The importance of this was stressed by the academician Legasov [15] in the early 1980s. Here again, mention should be made of an important, if not decisive role, of the "golden billion" countries. It might be expected that only these countries will primarily have conditions suitable for a legislative regulation of the transition to the Hydrogen Civilization. Having brought into use a judiciously chosen environmental tax on the consumption of hydrocarbon fuels, such a legislative regulating will provide financing of scientific, engineering and materials support for the establishment of the hydrogen energy system. In the initial stages, it will encourage hydrogen production and its consumption as an energy carrier. This will provide a stable economical basis for an eventual transition to the Hydrogen Economy.

As a result of the above, the legislative regulation of the economic development of large countries or groups of countries will eventually lead to an economic and environmental advantage of using hydrogen as an energy carrier; first, in the ecologically affected megalopolises and then on wider scales. Such will be the effect of a legislative-economic mechanism in the early stages of the transition to the Hydrogen Economy, and in the succeeding period of the Hydrogen Civilization. This transition will gradually attract the attention of countries with transforming economies, and later the developing countries.

Finally, to complete the presentation of this work, let us come up with two more basic ideas: (1) A transition to the Hydrogen Civilization in a historically given time will provoke both the Earth and humankind's geological existence to change; this will undoubtedly become the subject of special interest as a part of geology, as well as for other sciences, concerning the Earth, the only known planet that has a biosphere and life as we know it in its present form, and (2), the more effective international cooperation will speed up the conversion to the Hydrogen Civilization; in fact, such cooperative efforts may be the only way to reach a Sustainable State.

6. Conclusion

In this paper, for the first time, some planetary aspects of the humankind transition to the era of an ecologically clean Hydrogen Civilization are formulated and analyzed. The main reasons, which make people ponder and strive in this direction, are the rapid depletion of fossil fuels on one hand, and the global environmental problems caused by their utilization on the other, including an anticipated world-wide environmental disaster related to this effect.

A scientifically grounded way to solve all the environmental problems will be historically prolonged. A movement in this direction, touching all aspects of human society and the environment will lead to a change from hydrocarbon fuels to hydrogen energy, the latter being the only ecologically highly clean and efficient energy carrier.

Some biospheric and noospheric aspects of humankind's transition to Hydrogen Civilization have been analyzed. Some important possible stages of the transition to the Hydrogen Civilization have been indicated, including the important role of the scientific community, general public, international and regional organizations, and parliaments and governments of the world countries. It has been emphasized that these global changes in humankind's life need a long period of time, and legislative-economical self-regulation of the life of people and countries. The effective international cooperation would no doubt speed up the conversion to the Hydrogen Civilization and the attainment of a Sustainable Future.

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