SUSTAINABLE NON-ELECTRIC APPLICATIONS OF NUCLEAR ENERGY

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I. Introduction

Nuclear energy, while contributing 17% of electricity generation worldwide, currently contributes only 7% to primary energy. Except for electricity generation, with few exceptions (e.g., military ship propulsion), the diverse applicability of nuclear power which was envisioned at the start of the nuclear age has not yet been put into widespread practice.

Now, with emerging issues attendant sustainable development of world economics, nuclear's capacity to deliver heat which is free from carbon emissions offers renewed incentive to consider a broadened, non-electric, energy intensive product mix from nuclear energy.

In contemplating such an expanded role for nuclear in 21st century energy sustainability, it has been useful to consider energy supply infrastructures as a whole and the historical and projected future technological trends of the infrastructure elements (resource, conversion, and carrier). The intent has been to identify the future energy clients and their special energy product needs in the decades following 2030 so as to tailor the proposed sustainable nuclear energy supply concept to those perceived needs.[1]

The ideas discussed here are not new ones, but they are timely. The works of Marchetti,[2] Hafele,[3] Ausubel,[4] Nakicenovic,[5] Yoda,[6] and many others are the source of energy infrastructure ideas discussed below, and the reactor design concepts of the Integral Fast Reactor (Till, Chang, and others)[7] are adapted extensively.

Finally, it has been recognized that technology innovations, while necessary are not sufficient; institutional innovations will be necessary as well for nuclear to broadly expand worldwide. They are identified and discussed briefly.

II. Trends in Energy Infrastructures and Client Base

Energy availability and use drives society's economic development and quality of life. Today energy use per capita is markedly inhomogeneous. The richest 20% of global population use 55% of final energy; the other 80% of global population use 45% of final energy. Global energy demand growth in the 21st century, therefore, will be driven not only by population growth but especially by dramatic increases of energy intensity per capita as the economies and associated living standards rise in developing countries. Capacity additions will be dominated by additions made in developing economies – while at the same time the replacement market in industrialized nations will remain significant in light of the high baseline on which their modest growth is occurring. The indigenous infrastructures in many developing economies will initially be sparse and capital will in general be in short supply and over subscribed. This suggests a need for small increments in energy asset deployment, and that plants should be provided in modular size.

As to overall size of the market, energy demand projections released recently[5] by the IIASA/WEC employ several scenarios to attempt to encompass plausible outcomes over the coming decades. Realistic scenario assumptions concerning resource mix are used as well. Based
on these projections, it is found to be prudent to base our planning on a need for upwards of 2000 GW_e of nuclear plants by the year 2050. Since the number of required new plants is very large – especially for plants of ~0.1 GW_e/plant – we can consider a strategy relying on economy of mass production as a viable alternative to the traditional strategy for nuclear plants.

The more interesting trends in energy supply are occurring in the converter and carrier components of the infrastructure. As shown in the plot of time evolution of energy conversion efficiency (Fig. 1), it has increased from 1% to 50% in 300 years; it is currently at 50% using gas turbines and it can be anticipated that by 2020, fuel cells can advance this to 70% efficiency.[8]

Fuel cells are expected to find their first widespread application in the transportation sector (one-third of primary energy consumption). Anticipating emissions control limits, Daimler/Chrysler, Toyota, Ford, and other major vehicle companies are investing hundreds of millions to billions of dollars to bring fuel cell powered automobiles to market in the early decades of the century. The currently high capital cost (~1,500$/kw) of hydrogen-consuming fuel cells can be expected to be driven downward as a result of future massive production runs in the vehicle industry. But greenhouse gas emission reduction benefits of fuel cell usage will accrue only if the hydrogen fuel derives from a non-carbonaceous source – such as the cracking of water using nuclear generated electricity and/or heat.

While use of hydrogen to drive fuel cells vehicles is likely to emerge as the first new widespread market for hydrogen (beyond the current ammonia/fertilizer market), Fig. 2 reveals[9] the market inexorably trending over the past century and a half to hydrogen-rich/carbon-poor chemical energy carriers for the entire non-electric of the energy market. Based on this trend it is projected[9] that by 2030 methane will join coal and oil in market share decline and that hydrogen can be expected to hold the dominant market share of chemical energy carriers (complimentary with electricity) in subsequent decades.

The market trends in the carrier and converter segments of the world energy infrastructure suggest that the nuclear energy supply approach for the mid and later decades of the 21st century should couple to modern energy converters (gas turbines, fuel cells), and the energy carriers (electricity and hydrogen) predicted by market trend analysis to be contemporary at that time.

It is evident that using nuclear heat to manufacture synthetic chemical fuel such as hydrogen would facilitate the non-electric two-thirds of the primary energy market to benefit from the non-carbonaceous nuclear energy supply source and contribute to the sustainability goal of global greenhouse gas reduction. Transitions in energy supply infrastructure addressed to long-term sustainability will require that the basic energy resource itself (i.e., the earth’s endowment of actinide elements) must be sustainable even when deployed to fill a significant fraction of the market. While the reserves of U^{235} and of plutonium present in discharged fuel from current generation reactors will last for several decades, analyses[10] based on the energy demand scenarios[5] suggest that fast spectrum reactors capable of “burning” U^{238} and/or Th^{232} using recycle will be required by mid century owing to the (by then) scarcity of fissile U^{235} and or Pu^{239} from past thermal reactor operations. The world’s known reserves of affordable uranium and thorium are then capable of supporting projected needs for several millennia.
To summarize, energy market trend analyses suggests that a strategy for nuclear energy to play a significant role in 21st century energy sustainability would be to target modular sized plants for the market in developing countries and to expand beyond electricity production into production of hydrogen as a synthetic chemical energy carriers. A hydrogen based global energy supply infrastructure was proposed in the 1970s as the sustainable solution for global growth[2] – long before sustainability reached its current level of governmental attention. This visionary infrastructure relies on solar and nuclear fission for the essentially infinite energy resource, complete fission consumption of the basic actinide resource, and on electricity and hydrogen (generated by cracking water) as complimentary dual energy carriers. Fission products having an ~300 year toxic lifetime are the only waste emerging from the energy supply infrastructure because the hydrogen burning product recycles as water and greenhouse gas emissions are altogether avoided. Since the 1970s, market forces have (or soon will) emplace the requisite energy converters and carriers; specifically, the energy converters in widespread use in the decades ahead will be fuel cells, combustion gas turbines, and electric motors, and a partially developed hydrogen distribution system should be in place imminently to service the transportation sector. Only the sustainable resource segment of the envisioned infrastructure remains to be emplaced; nuclear should position itself to play a significant role there, perhaps in concert with solar.

III. Meeting Energy-Intensive Sustainability Needs with Nuclear Process Heat

The hydrogen/electric energy architecture, already presaged thirty years ago, quite obviously favorably addresses the now intensely discussed definition of sustainable development:

Sustainable development defined as “development that meets the needs of the present without compromising the ability of future generations to meet their own needs.”

It addresses the essential inexhaustibility of the basic energy resource $\text{U}^{238}$, $\text{Th}^{232}$, and sunlight, and it achieves the near total elimination of greenhouse gas emissions and the responsible minimization of solid radioactive waste mass and the duration of its toxicity. Moreover, this architecture unfetters the nuclear energy resource from its -- up to now -- exclusive applicability to the one-third electricity segment of primary energy need, so as to (via synthetic chemical fuel, hydrogen) apply greenhouse-gas-free fission energy to the much larger (two-thirds of primary energy) segments of societal energy use.

By further expanding the menu of energy-intensive products produced using nuclear process heat, other sustainability needs of society could also be addressed. Of particular note is the impending need by 2030 and beyond for potable water. The World Bank has estimated that a billion people currently have poor access to clean drinking water; and by 2025 that number will more than double. The problem is most intense in large cities, the focus of demographic migrations; where the need to provide and maintain both supply source and delivery infrastructure applies equally in developing and developed economies. Unlike electricity, water, similar to hydrogen, is a storable energy commodity ideally suited for base loading the costly nuclear supply assets and for flexibly diversifying resulting energy-intensive saleable product
mix. Additionally, the distribution infrastructures for hydrogen and for water are suited for regional scale, and they similarly rely on networks of pipeline easements. Drinking water supply is currently a $400 billion a year industry[11] and has been predicted to be, for the 21st century what the oil industry was for the 20th. Boiling water is what nuclear currently does well. In future, manufacture of potable water from cheap or free brackish or salt water to provide the feedstock to the water cracking hydrogen production plant as well as for sale as a valuable commodity should become a natural additional contribution from nuclear for meeting society's sustainability needs.

Megacities – urban centers of many millions of residents living and working in areas in high population density – are an inevitable feature of industrialization and present unique challenges for sustainability because of highly dense flows of energies, effluents, and other commodities required for human activity. One especially important aspect is the issue of air quality and the need to reduce and/or mitigate air-borne emissions – not just from transportation, but from home heating, cooking, and from industrial uses of energy as well. Because its combustion releases no greenhouse gases and NOx emissions can be minimized, hydrogen will likely find growing market opportunities as a pollution free chemical fuel in a broad scope of applications – especially in urban areas.

A second issue of energy infrastructures for megacities is the sheer magnitude of the supply and distribution challenges – with needs (a) for sources to be located near the demand center, (b) for a forward storage of energy resource against the possibility of supply disposition, and (c) for diversity and redundancy of distribution channels to reduce opportunities for massive disruptions in the event of natural events or equipment failures. While the extraordinary energy density of nuclear fuel well satisfies a need for energy security, siting nuclear power plants near megacity demand centers will likely require increasingly stringent safety standards on the plants and favor the increasing application of “passive” or “deterministic” safety strategies in plant design. Given success in siting near load centers, additional energy services could be provided by nuclear energy – specifically district heating and process heat supplies to industrial eco parks.

District heating using bottoming cycles on nuclear-electricity supply plants is already an industrial scale technology – practiced extensively in the republics of the former Soviet Union. The grid network of supply pipes could in some cases develop naturally alongside those for hydrogen and potable water.

The application of nuclear process heat in industrial eco parks where a diversity of industries cluster around an energy source to symbiotically exchange flows of materials and energy in such ways as to minimize effluent waste streams and maximize economic output may well provide an important transition pathway to long-term sustainability. In the deregulated utility markets which are becoming common in western industrialized nations, numerous opportunities should exist for the fossil and nuclear sectors to find mutually supportive (symbiotic) arrangements, which help both sectors achieve the transition to energy sustainability. For example, as multinational oil and gas conglomerates transition to become energy conglomerates, the nuclear community should develop schemes for nuclear heat assisted reforming or pyrolysis of fossil fuel to increase hydrogen yield per unit of CO2 release from the fossil resource. As energy parks transition to become multi-industry eco parks, with mutual
exchange of mass and energy flows, opportunities will emerge for applications of greenhouse-gas-free nuclear heat delivered over the full range of temperature from ambient to the highest temperature reachable by the technology of that decade (see Fig. 3).

III. Strategic Approach to Broaden Nuclear’s Role in Energy Sustainability

The trends toward decarbonization of chemical fuels, transportation sector reliance on hydrogen burning fuel cells, potable water as a valuable commodity and a dual energy carrier infrastructure based on grid delivery of electricity and hydrogen – (perhaps with distributed final energy conversion based on microturbines and fuel cells decentralized to a neighborhood level of granularity) – these will occur under the influence of market forces over the coming decades, and although major infrastructural changes such as those described require decades to complete,[12] it is only sensible to take note of these trends in planning the role and configuration for nuclear power in 2030 and the ensuring decades. A strategy for ensuring that nuclear energy can contribute to global energy sustainability rests on anticipating the outcome of these trends and initiating the R&D required to position the sustainable nuclear energy resource so that it can in the future service the emerging client base for process heat and couple to advanced energy conversion and carrier infrastructure elements.

R&D has been initiated at numerous institutions worldwide on nuclear energy concepts intended to fill the broadened scope of clients and energy services outlined above. Many of the concepts are based on modular sizing. Some employ very long refueling interval at the client’s site -- with front and back end services provided from a regional supplier’s site servicing numerous regional clients. Such sites oftentimes are proposed to be operated under international oversight. Along with electricity production at the 50 to 150 MWₜ plant size, desalinization, process heat applications, and hydrogen production are common themes in these R&D programs.

In the near- to mid-term, the technologies are already in place and should be exploited to apply nuclear energy based on thermal spectrum reactors and fuel cycles to the development of the hydrogen economy. Electrolysis during periods of off peak electricity load[17] and near- to mid-term use of high temperature gas reactors for process heat and water cracking[18] are two examples.

Eventually, however, fast spectrum reactors consuming U²³⁸ and/or Th²³² will be necessary for achieving sustainability. The transition period of 20 to 40 years during which the new infrastructure establishes itself should be ample to accomplish the required technical and institutional innovations to add the sustainable fast reactor and recycle elements to the mix. While ample, a sense of urgency in starting the innovation efforts is warranted. Trending projections forecast that the current glut of fissile inventory will be consumed by the mid century. Therefore, by that time it is essential that a substantial number of the fast spectrum reactors and associated recycle facilities should already be in place such that their reload cores can be reconfigured from fissile self sufficient to breeding configurations so as to manufacture fissile to supply the working inventories of new installations in the growing economy. In the event that fissile shortfalls were to occur, dedicated fissile manufacturing systems located at the regional service centers could be emplaced. The applicability of fast spectrum subcritical source-driven systems – having a remarkable excess neutron balance – to manufacture fuel for thermal
reactors of low fissile working inventory might find a role should the fissile price escalate sufficiently due to shortages.

Institutional innovations will also be necessary to establish international consensus and norms. Such norms in the areas of safety, safeguards, indemnity, etc. are necessary both for extensive deployment of plants worldwide and for the deployment of regional front and back end service centers providing the nuclear fuel fabrication, refueling services, and back end recycle and waste management activities — all conducted under international oversight. Such services would be provided only to those clients who agree to abide by the portfolio of safety, safeguards, liability, radiation safety, emissions, and etc. norms and who perhaps share in ownership and operation of the regional centers. That such international norms can be achieved is evident by past successes in the areas of safeguards regimes, safety norms, indemnification norms, radiation exposure standards, and etc. Building international consensus none-the-less takes substantial resolve and many years of effort and should be initiated coincident with the technology R&D.

IV. Acknowledgments

Bruce Spencer, Richard Doctor, Hussein Khalil, Bob Hill, Dave Hill, Dave Lewis, Vladimir Kagramanian, and Masao Hori have provided many stimulating and valuable critiques during the process of refining ideas on the subject of nuclear's broadened role in energy sustainability.

The notions presented here represent the author's viewpoint and do not constitute an official Argonne position.

REFERENCES


FIG. 1. Improvement in the efficiency of motors and lamps analyzed as a sigmoid (logistic) growth process. NOTE: Shown in a linear transform that normalizes the ceiling of each process to 100%. MAIN DATA SOURCES: for lamps, Encyclopedia Britannica (1964); for motors, Thirring (1958). Copyright 1997 by the National Academy of Sciences.

FIG. 2. Ratio of hydrogen (H) to carbon (C) for global primary energy consumption since 1860 and projections for the future, expressed as a ratio of hydrogen to carbon (H/C). SOURCE: Ausubel (1996) and Marchetti (1985). Copyright 1997 by the National Academy of Sciences.
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**FIG. 3.** Temperature region of heat used in various kinds of industries.