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Why nuclear energy is sustainable and has to be part of the energy mix ☆

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ABSTRACT

Humanity must face the reality that it cannot depend indefinitely on combustion of coal, gas and oil for most of its energy needs. In the unavoidable process of gradually replacing fossil fuels, many energy technologies may be considered and most will be deployed in specific applications. However, in the long term, we argue that nuclear fission technology is the only developed energy source that is capable of delivering the enormous quantities of energy that will be needed to run modern industrial societies safely, economically, reliably and in a sustainable way, both environmentally and as regards the available resource base. Consequently, nuclear fission has to play a major role in this necessary transformation of the 21st century energy-supply system.

In a first phase of this necessary global energy transformation, the emphasis should be on converting the major part of the world's electrical energy generation capacity from fossil fuels to nuclear fission. This can realistically be achieved within a few decades, as has already been done in France during the 1970s and 1980s. Such an energy transformation would reduce the global emissions of carbon dioxide profoundly, as well as cutting other significant greenhouse gases like methane. Industrial nations should take the lead in this transition.

Because methane is a potent greenhouse gas, replacing coal-fired generating stations with gas-fired stations will not necessarily result in a reduction of the rate of greenhouse-gas emission even for relatively low leakage rates of the natural gas into the atmosphere.

The energy sources popularly known as 'renewables' (such as wind and solar), will be hard pressed to supply the needed quantities of energy sustainably, economically and reliably. They are inherently intermittent, depending on backup power or on energy storage if they are to be used for delivery of base-load electrical energy to the grid. This backup power has to be flexible and is derived in most cases from combustion of fossil fuels (mainly natural gas). If used in this way, intermittent energy sources do not meet the requirements of sustainability, nor are they economically viable because they require redundant, under-utilized investment in capacity both for generation and for transmission.

Intermittent energy installations, in conjunction with gas-fired backup power installations, will in many cases be found to have a combined rate of greenhouse-gas emission that is higher than that of stand-alone coal-fired generating stations of equal generating capacity. A grid connection fee, to be imposed on countries with a large intermittent generating capacity, should be considered for the purpose of compensating adjacent countries for the use of their interconnected electric grids as back-up power. Also, intermittent energy sources tend to negatively affect grid stability, especially as their market penetration rises.

The alternative — dedicated energy storage for grid-connected intermittent energy sources (instead of backup power) — is in many cases not yet economically viable. However, intermittent sources plus storage may be economically competitive for local electricity supply in geographically isolated regions without access to a large electric grid. Yet nuclear fission energy will, even then, be required for the majority displacement of fossil fuels this century.

1. Introduction

In the long history of human economic activity prior to the nineteenth century, the only available energy capable of replacing human

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labor was derived from falling water, wind and domesticated animals consuming local vegetation. As a source of heat, humanity relied on burning biomass, i.e., wood, peat and cow dung. The large-scale use of fossil fuels with compact chemically stored energy started in the early eighteenth century, with combustion of coal being the driving force behind the steam engine and consequently the industrial revolution. This use of fossil fuels (initially mainly lignite and coal; later oil and natural gas) has served humanity well during the historically short time period of about two centuries, having allowed the world population, with its supporting agricultural and industrial productivity, to grow to previously unimaginable numbers while providing an average standard of living that is higher than ever before.

But will it be possible to always use fossil-fuels at a rate that is equal to or higher than current consumption? From a historic perspective, the past two hundred years of large-scale use of fossil fuels is a very short time period. Independent of the importance placed on anthropogenic climate change, one inevitably comes to the conclusion that a change in energy supply is necessary. Thus, the real question is not whether change must occur, but on what time scale does this change have to take place. There exist numerous pressing reasons why change has to come soon, including (a) continued large-scale combustion has many deleterious human-health and environmental consequences, (b) extraction of fossil fuels will become increasingly difficult, costly and energy-consuming so that the energy gain will become smaller (i.e., energy obtained vs. energy invested) and (c) fossil fuels constitute a finite and valuable resource for non-energy-related industrial and manufacturing processes, and so should be used sparingly and preserved for future generations. Even the strongest opponents of change and those that dismiss the risk of anthropogenic global warming will understand that it is simply not possible to continue indefinitely in the coming centuries as before when considering that a large part of the easily recoverable fossil fuel resources have already been extracted during the past two hundred years.

Clearly, global society must start to taper off its dependence on the large-scale combustion of fossil fuels, initiating a new *modus operandi* aimed at restricting the use of fossil resources mainly to residential use and to feedstock for industrial (chemical) purposes. Industrial nations should take the lead in this change because they are more capable of doing so, having already developed the necessary technological and mature economic base. Yet such a major transformation of the energy supply system cannot be accomplished within a few years without severe deleterious economic consequences that could well have devastating consequences for humanity as a whole. Instead it has to be introduced in a gradual and systematically planned way that causes the least disruptions.

The energy consumption in industrial nations may be divided in three roughly equal parts, namely for (a) electric energy generation, (b) industrial process heat and space heating and (c) transportation. Nuclear energy is already widely deployed for electrical-energy generation. Therefore, the least disturbing and most logical way to start reducing fossil-fuel consumption would be increasing the use of nuclear power plants for electricity supply. It would be well within realistic limits to aim for replacement over a time period of several decades of the major part of the world's fossil-fuel-based electrical-energy generating capacity. In parallel to this major change in electrical energy generation, the use of fossil fuels for transportation should be reduced by greater reliance on both nuclear-derived electrical energy and liquid fuels produced synthetically by means of nuclear power plants. Also the use of nuclear-derived process heat for industrial application should be encouraged.

2. History, development and sustainability of nuclear energy

The practical generation of nuclear energy was demonstrated on the second day of December 1942 when the first human-controlled self-sustaining nuclear fission reaction was achieved at the University of Chicago under the guidance of Italian-born physicist Enrico Fermi. This experimental reactor (in those days called an 'atomic pile') made use of 'slow' (usually called 'thermal') neutrons, capable of sustaining a chain reaction in the rare 'fissile' uranium isotope U-235 that constitutes only 0.7% of natural (mined) uranium; the rest (99.3%) being the 'fertile' isotope U-238. From this small experimental reactor, an entire industry emerged that has led to 435 operating nuclear power reactors (as of late 2014), 72 under construction, and 174 more on order or planned, as well as numerous research reactors around the world, delivering clean energy and a large number of products and services for use in many human activities, including medical diagnosis/therapy, industry and agriculture. While all of these applications and products have become of utmost and growing importance in supporting our standard of living and health, this article will deal solely with the application of nuclear fission reactors for the production of energy.

Nuclear energy derived from fission of uranium and plutonium (transmuted from U-238) is capable of replacing most, if not all, of the stationary tasks now performed by the combustion of fossil fuels (thorium might also have a future application). However, many environmental organizations and governments have opposed, and continue to oppose, the application of abundant nuclear energy. Among the reasons usually given against nuclear fission energy are that it is: (a) unsustainable; (b) uneconomic; (c) unsafe and (d) has links to proliferation of nuclear weapons. Below each of these key concerns is addressed.

Two important questions that need to be asked are: Is nuclear energy sustainable, and would it be possible to replace fossil-fuel derived energy with 'renewables' (e.g., wind- and solar energy), as is advocated by many governments and environmental organizations? To answer these questions, it is necessary to ask what is understood by the term 'sustainable'. The term 'sustainable' is generally understood to mean "*meeting the needs of the present without compromising the ability of future generations to meet their own needs*" [1]. In the context of energy options, 'sustainable' implies the ability to provide energy for indefinitely long time periods (i.e., on a very large — civilization-spanning — time scale) without depriving future generations and in a way that is environmentally friendly, economically viable, safe and able to be delivered reliably. It should thus be concluded that the term 'sustainable' in this context is more restrictive than the term 'renewable' that is often applied to energy derived from wind, sunlight, biomass, waves, tides and geothermal resources, which for certain applications do not meet all the criteria of sustainability (as discussed later).

Nuclear energy from fission of uranium and plutonium is sustainable because it meets all of the above-mentioned criteria: Today's commercial uranium-fueled nuclear power plants can provide the world with clean, economical and reliable energy well into the next century on the basis of the already-identified uranium deposits (Table 1). Furthermore, as was pointed out by Enrico Fermi already in the 1940s, nuclear reactors operating with 'fast' neutrons are capable to fission not only the rare isotope U-235 but also the fissionable isotopes generated from the transmutation of the abundant 'fertile' isotope U-238 (or Th-232). Thus the use of fast-neutron fission reactors (usually called 'fast reactors') transforms uranium into a truly *inexhaustible energy source*, because of their ability to harvest about one hundred times more energy from the same amount of mined uranium than the commercially available 'thermal' reactors operating with thermal neutrons [2,3]. This fast-neutron fission technology has already been proven — all that is needed is to develop it to a commercial level and deploy it widely [4] (for an extended discussion on the critical need for a near-term fast-reactor deployment, refer to a companion paper in this journal). The amount of depleted uranium (i.e., uranium from which most of the 'fissile' isotope U-235 has been removed) that is available and stored at enrichment plants in a number of countries, together with the uranium recoverable from used-fuel elements, contains enough energy to power the world for several hundred years without additional mining.