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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.

Table 1
Uranium reserves in countries with more than 1% of proven world reserves.
Source: OECD. Uranium 2009: Resources, Production and Demand. OECD NEA Publication 6891. 2010.

Country	Reserves as of 2009	World share	Historical production up to 2008	World share
Australia	1,673,000	31.0%	156,428	6.5%
Brazil	278,700	5.2%	2839	0.1%
Canada	485,300	9.0%	426,670	17.7%
China	171,400	3.2%	31,399	1.3%
India	80,200	1.5%	9153	0.4%
Jordan	111,800	2.1%	0	0.0%
Kazakhstan	651,800	12.1%	126,900	5.3%
Namibia	284,200	5.3%	95,288	4.0%
Niger	272,900	5.0%	110,312	4.6%
Pakistan	80,900	1.6%	1159	0.0%
Russia	480,300	8.9%	139,735	5.8%
South Africa	295,600	5.5%	156,312	6.5%
Ukraine	105,000	1.9%	124,397	5.2%
United States	207,400	3.8%	363,640	15.1%
Uzbekistan	114,600	2.1%	34,939	1.4%
Vietnam	140,800	2.2%	0	0.0%

Afterwards, mining of small quantities of uranium in future centuries, including extracting uranium from lower-grade ores and — if necessary — from seawater, could satisfy global energy needs economically for as long as human civilization will endure [3].

In conclusion, the fuel supply side of nuclear power reactors does not give reason for any doubt concerning its sustainability. As to the materials used in the construction of nuclear power plants, none are in short supply (and most are readily recyclable), so that they too do not constitute a sustainability impediment.

3. Economic viability

Nuclear energy is capable of economic viability, as has been shown (for instance) in the national energy program in France, where the unit price of electricity in a market supplied about 75% by nuclear fission is among the lowest worldwide. After the oil boycott of 1973, France decided that it needed to strive for greater energy independence. Over a time period of about two decades, France converted the major part of its electrical energy generating capacity from fossil-fuel-based to uranium-based. The cost of the nuclear power plants was kept low by producing them in a series of identical units and by minimizing the needed changes that were implemented in a coordinated way in all plants of a given series. In addition, delays during construction (that could have been very costly) were prevented by careful preparations by both the government and the utility (including good public information and an efficient licensing process, focused sharply on the significant safety issues). An important additional benefit of this reliance on nuclear energy is that per-capita emission of greenhouse gases in France is among the lowest for industrial nations worldwide and many times lower than in otherwise similar countries that have no nuclear power plants and that rely on a mix of fossil fuels and some contribution from renewables (e.g. Australia, Denmark).

Important conditions for economic viability of nuclear energy are: (1) presence of a 'level playing field', i.e. an open market that is not skewed in favor of some technologies by means of subsidies and/or by a legally imposed priority access for delivery to the electrical grid at a fixed high price that are unavailable to nuclear; (2) standardization of the plants, built in large series and supported by a standardized supply chain; (3) a long-term governmental energy policy (stable over a time period of several decades) including, among other features, good (unbiased, accurate, evidence-based) public information; (4) a stable and streamlined licensing process that is technology-neutral, risk-informed and capable of resolving promptly any safety issues that may arise during construction and operation, (5) careful siting considerations to avoid areas most prone to severe natural hazards, and (6) introduction of the concept of payment for 'external costs' (e.g. air pollution, solid wastes, decommissioning) that is applied to all energy technologies based on common standards.

Many countries promote wind and solar energy with the aim of reducing greenhouse-gas emissions. This is done in part by giving them priority access for delivery to the grid. This means that other generating plants are forced to ramp output up and down to cope with the intermittency of these inherently varying sources. This mode of forced 'accommodative' operation penalizes nuclear power plants more than it does fossil-fired plants because the capital–cost component of the generating cost for the former is relatively high and the fuel cost component is low, whereas for the latter the reverse is true, especially for open-cycle natural-gas plants (Table 2). This practice of distorting the energy market has serious and undesirable consequences, resulting in closure of base-load generating capacity (including nuclear power plants), loss of grid reliability and higher net greenhouse gas emissions. Nuclear power plants are able to adapt to this load following mode (even though this is not recommended for economic reasons) as long as the percentage of intermittent sources is low, as has been proven in France [5]. To compensate for the negative economic effect on base-load plants, a 'grid service' tariff is applied in France to quantify the cost of the supply-intermittency caused by wind and solar.

An important aspect of long-term commercial viability of power plants is the future development of their respective fuel costs. Nuclear power plants rank best in this respect because their sensitivity to fuel-cost increases is small (Table 3). A temporary abundance of low-cost natural gas may seem to make gas-fired stations appear to be economically attractive. However, this will change because it can be expected that gas prices will rise substantially during the 60 + lifetime of new-build nuclear power plants.

Nuclear energy is not limited to the generation of electricity, but may equally well be used for such important tasks as desalination, production of hydrogen, space heating and process-heat applications in industry as well as for extraction of carbon from CO_2 to combine with hydrogen to create synthetic liquid fuels. Many of these alternative applications of nuclear energy will combine very well with the generation of electrical energy in that the reactors could be operated continuously at full power, allocating the required amount of heat to satisfy the electrical load demand and the rest for producing fresh water, hydrogen or steam for industrial processes [6]. Many areas around the world are already facing severe shortages of fresh water and it can be expected that the need for fresh water will be ever increasing. Nuclear-energy-driven desalination in coastal regions will be able to satisfy part of this need. Alternatively, nuclear power plants will be able to provide the

Table 2
Generation cost breakdown.
Source: OECD — International Energy Agency: World Energy Outlook 2005.

	Nuclear (%)	Coal (%)	Gas (%)
Capital	59	42	17
Fuel	15	41	76
Operation & maintenance	26	17	7

Table 3
Fuel price increase sensitivity.
Source: WEO '06/OECD IEA World Energy Outlook 2006.

Impact of a 50% increase in fuel price on generating cost			
Nuclear	IGCC[a]	Coal steam	CCGT[b]
3%	20%	22%	38%

[a] IGCC = integrated gasification combined cycle coal.
[b] CCGT = combined cycle gas turbine.

energy to pump fresh water from areas with a surplus to regions facing a shortage.

4. Environmental considerations

As numerous scientific comparisons have shown, nuclear fission is among the energy sources that are least polluting and have the lowest overall environmental impact [7]. Operating nuclear power plants do not produce air pollution nor do they emit CO_2. Annually, the 435 operating nuclear power plants prevent the emission of more than 2 billion tons of CO_2. By contrast, coal-fired stations emit worldwide about 30 billion tons of CO_2 per year and cause health effects and premature death through air pollution and dispersion of pollutants, including mercury (harmful to the nervous system, particularly for infants) and other poisonous materials [8]. It is important to note that nuclear power plants emit less radioactive material than do coal-fired stations (uranium and other radioactive isotopes are found naturally in coal ash and soot) [9]. The most severe environmental impact associated with nuclear energy is due to the mining of uranium. However, the need for uranium mining will be drastically reduced after fast reactors have become commercially available, as may be expected within the coming decades.

New methods for efficiently recycling the used fuel (already proven and currently in an advanced stage of development for commercial application) will drastically reduce the radioactive hazards as well as the volume of the waste that must be kept isolated from the environment. As an example, the level of radioactivity of a repository containing this type of waste will, after about 300 years, be comparable to that of the natural uranium deposits that are widely distributed around the world. Furthermore, modern waste isolation technology will equal or exceed the level of isolation originally provided by nature for radioactive ores. In this way, the much-publicized radioactivity issue of the waste will be reduced to a historical time scale of a few hundred years, rather than a geological time scale of hundreds of thousands of years. It is important to note that this waste will be disposed of in an environmentally inert form, i.e., ceramic or vitrified solids that will not start leaching any material into the environment for thousands of years, long after their radioactivity will have dissipated. On the other hand, large amounts of solid and gaseous waste from coal-fired stations (including mercury and heavy metals) will remain poisonous in perpetuity and are not kept well separated from the environment.

The cooling water requirements of current commercial nuclear power plants (light-water reactors — LWRs) are slightly higher than those of fossil-fueled power plants because of the lower operating temperature of the former. However, the new generation nuclear power plants (liquid-metal-cooled fast reactors — LMFRs) will have operating temperatures equal to those of fossil-fuel-fired power plants and thus will have about the same cooling water requirements as those of fossil-fuel-fired plants. It should be pointed out that power plants (both nuclear and fossil-fuel-fired) usually do not 'consume' cooling water; they only heat up the water and return it as chemically and radioactively 'clean' as before to its origin, be it river, lake or sea. Only in the case that cooling towers are used, is water evaporated and returned to nature as clean water vapor (Table 4). Some power plants with cooling towers make use of city waste water which is first cleaned and then returned to nature in the form of clean water vapor. In this latter way of cooling, no demand is made on water that could be used for any other useful purposes. In locations where no water is available heat rejection to the air could be implemented. This would, however, entail a penalty on thermal efficiency, depending on the temperature of the air.

It is expected that the current temporary abundance of inexpensive natural gas due to the new 'fracking' technology, will be of short duration (perhaps about 50 years). The current supply rate of natural gas cannot be sustained in the long term if it continues to be burned in large and increasing quantities [10]. Natural gas is an irreplaceable resource that should be used sparingly and preserved for future generations. Its use for the generation of electrical energy is particularly wasteful in that up to 60% of the heat is being discarded by heating the cooling water or by evaporation in the cooling towers. A better application of natural gas is residential heating in which nearly full use is made of the combustion heat. While combustion of natural gas emits less CO_2 than coal, it nevertheless emits substantial amounts of CO_2 and is often accompanied by leakage of gas (sometimes quite substantial) resulting in release of methane (a potent greenhouse gas) into the atmosphere. If the aim is to lower the rate of greenhouse gas emission, natural gas use and leakage must be reduced.

Another consideration is that the world supply of helium is inextricably connected to the availability of natural gas. The reason is that helium accumulates subterraneously in conjunction with natural gas over hundreds of millions of years as a consequence of decay of uranium and thorium. Once the easily recoverable global resources of natural gas have been exhausted, humanity will also have eliminated its supply of relatively inexpensive helium. Helium is an important industrial gas that, among others, finds application as the coolant-of-choice in high-temperature gas-cooled nuclear reactors that probably will be deployed in the future for industrial processes requiring very high temperatures.

5. Safety

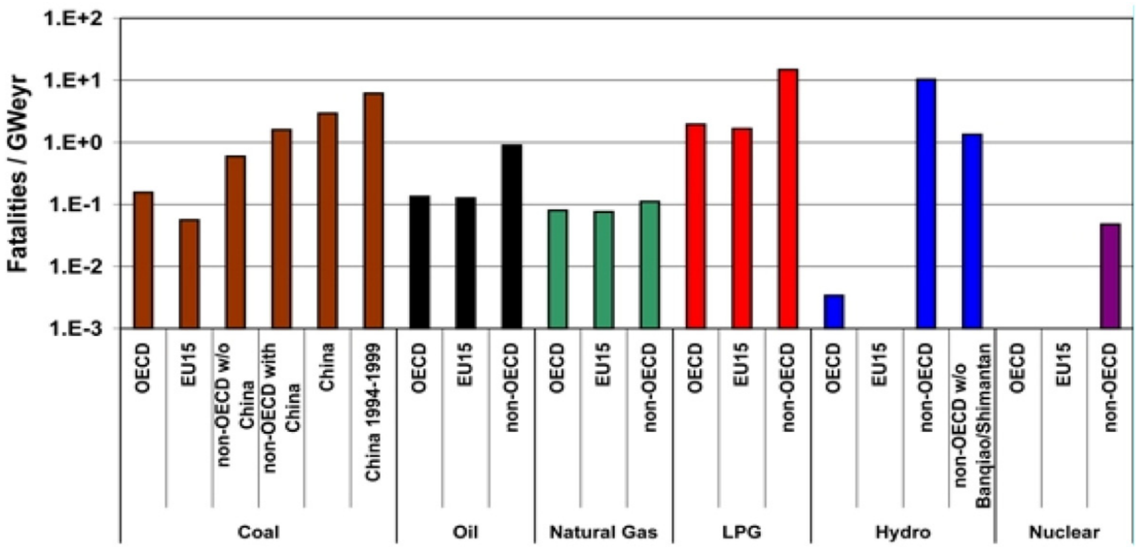
In spite of media-inspired misconceptions, nuclear fission is among the safest energy technologies in terms of health effects and fatalities (Tables 5 and 6). This is true notwithstanding the three major nuclear accidents that have occurred, namely at Three Mile Island (TMI) in the U.S.A., at Chernobyl in Ukraine, and at Fukushima in Japan. Of these three, only the Chernobyl accident caused a number of fatalities, namely among those persons that were directly exposed to high radiation doses during the urgent initial part of the cleanup operation. However, the number of these fatalities is relatively small (less than one hundred) if compared to the number of annual fatalities in the coal and oil/gas industry [7]. As an example, global average values of the mortality rate per billion kWh, due to all causes as reported by the World Health Organization (WHO), are 100 for coal, 36 for oil, 24 for biofuel/biomass, 4 for natural gas, 1.4 for hydro, 0.44 for solar, 0.15 for wind and 0.04 for nuclear (Table 6).

Both the accident at Chernobyl and that at Fukushima caused considerable land contamination and required evacuation of the population. However, in both cases the major part of the evacuated areas has/had radiation levels that are lower than the normal background level in many regions around the world, raising the question of how much evacuation — and for how long — was/is really necessary. In the case of Three Mile Island, there was no land contamination, but a

Table 4
Cooling water requirements of 1000 MWe plants (million liters/day).

Type of cooling	LWR (or typical coal plant) with 32% thermal efficiency	LMFR (or fossil-fuel-fired plant) with 42% thermal efficiency
Once-through cooling (temp. rise = 12 °C)	3690	2330
Cooling towers	81.2	52.8

Table 5
Comparison of energy-related damage (fatalities per gigawatt year), based on historical experience of severe accidents that occurred in OECD countries, non-OECD countries and EU-15 (fifteen European countries).
Source: Paul Scherrer Institut, Technology Assessment, Risk Assessment, http://gabe.web.psi.ch/research/ra.



short-term evacuation was imposed as a precautionary measure. It should be noted that land contamination is not limited to severe nuclear accidents; it is a repeated event in the chemical industry, in which the contaminants often are extremely deadly and long lasting (Bopal, India; Seveso, Italy).

The radioactive isotopes of iodine (I-131, half-life about 8 days) and cesium (Cs-137, half-life about 30 years) have dominating importance in accidents in which the containment is breached and radioactivity is released into the environment. I-131 will decay relatively quickly to zero and simple precautions can prevent its health effects. However, Cs-137 will stay in the environment for a longer time period that is determined by its biological half-life, i.e. the combination of its radioactive half-life and the rate of removal from body tissues or the soil surface by natural processes. This latter process can be accelerated by removal of a thin layer of the top soil in areas where the radiation level exceeds the allowable radiation level, as was successfully done in Goiania, Brazil, where a medical radioactive cesium source had been abandoned and subsequently breached with the content being spread into the surrounding area. Any contamination with radioactive materials can be remediated in the same way as done for spills of chemical materials.

Table 6
Mortality rates for each energy source in deaths per billion kWh produced.
Source: Updated (corrected) data from: World Health Organization; CDC; Seth Godin; John Konrad.

Energy source	Mortality rate (deaths per billion kWh)
Coal — global average	100 (50% of global electricity)
Coal — China	160 (75% of China's electricity)
Coal — U.S.	15 (44% of U.S. electricity)
Oil	36 (36% of global energy, 8% of global electricity, none in U.S.)
Natural gas	4 (20% of global electricity)
Biofuel/biomass	24 (21% of global energy)
Solar (rooftop)	0.44 (<1% of global electricity)
Wind	0.15 (~1% of global electricity)
Hydro — global average	1.4 (15% of global electricity, 171,000 Banqiao dead)
Nuclear — global average	0.04 (17% of global electricity, with Chernobyl & Fukushima — none in US)

Natural background radiation varies greatly over the world (depending on soil composition and the location's elevation) but higher background has not been found to be correlated with higher rates of cancer in the population. The average background radiation at sea level in much of the world is about 3 millisievert (mSv) per year whereas that in many regions around the world is considerably higher. As an example, at Ramsar in Iran the background radiation level is about 138 mSv per year, i.e. about 46 times higher than the average background. Yet the incidence rate of cancer in the local population of these regions with high background radiation has not been observed to be higher than normal.

When addressing nuclear safety, it is important to make a clear distinction between public safety and economic damage. There is no doubt that the economic damage associated with nuclear accidents can be substantial, as was demonstrated in the above-mentioned three major accidents. This potential for severe economic damage should be (and is) a strong incentive on the part of the owner/operator of the nuclear power plant to observe extreme caution, observing strictly all safety-related rules and regulations and maintaining a strict safety culture (even without being continuously monitored by the relevant regulatory organization).

As is normal in the evolution of any technology, also the new designs of nuclear power plants incorporated many safety-related improvements (even though the safety level in older plants is already very high in comparison with other large-scale electricity generating technologies). For example, the calculated probability of the occurrence of damage to the nuclear core for a new-generation nuclear power plant is typically about one hundred times less than that of early plant designs. An indicator of the high level of safety of new-generation plants is that, even in the case of the most serious design-basis accidents, the general public will not have to be subjected to any emergency actions (no off-site countermeasures are required). Even for postulated very severe accidents in which the reactor core is assumed to be completely destroyed, dedicated safety systems will limit both the consequences and the duration of the emergency. Moreover, advanced technology is focused on inherently 'passive' safety, rather than on actively operated engineered safety systems requiring externally supplied energy.

Public opposition to nuclear energy is in part due to fear of radiation caused by memories of the effects of nuclear weapons used during

World War II and by sensationalized coverage by news media of nuclear incidents. However, it should be stressed that nuclear power plants are physically absolutely incapable of exploding in the same way as nuclear weapons because the composition of the nuclear core (consisting mainly of U-238, zirconium and water) does not permit this. The explosions that were observed during the accident at Fukushima were chemical in nature, caused by the formation and accumulation of hydrogen (and its subsequent chemical explosion) due to overheating of the nuclear reactor core triggering the oxidation of the zirconium in the cladding of the fuel rods by hot steam.

One cause of the public fear of radiation is the use of the scientifically unsubstantiated Linear-No-Threshold (LNT) hypothesis in which it is erroneously assumed that the biological effects of nuclear radiation are linear with dose over a range of some five orders of magnitude, i.e., even at very low levels [11–13].

6. Potential diversion of weapons-grade materials

Production of nuclear weapons requires access to weapons-grade materials, i.e., either the isotope Pu-239 or the isotope U-235. Both these isotopes have to be of high purity. The isotope Pu-239 is obtained by irradiation of U-238 (neutron capture), whereas the isotope U-235 is produced from natural uranium by enrichment, i.e., separation of U-235 from the mined 'natural' uranium.

Most countries have signed the Non-Proliferation Treaty, committing them to refrain from producing weapons-grade materials and nuclear weapons. The main task of the International Atomic Energy Agency (IAEA) is to verify adherence by the member states to the Non-Proliferation Treaty. IAEA has fulfilled this task well and continues to do so.

No currently operating commercial nuclear power reactor has ever been used for the production of weapons-grade materials, with the exception of the dual-purpose RBMK-type reactors that were constructed in the Soviet Union. One of the reasons that commercial nuclear power reactors have not been used for the production of Pu-239 is that one strives for economic reasons in nuclear power plant operation to achieve a high 'burnup' of the fuel, i.e., a high percentage of the U-235 and Pu-239 atoms have undergone fission. Because of this high burnup, a large fraction of the U-238 is transmuted into higher isotopes of plutonium; the consequence of this is that the material that can be chemically extracted from the used fuel is either not useable at all for weapons or is of very low quality. The best weapons-grade material is produced from low burnup fuel and is usually extracted from depleted uranium irradiated in reactors that have been especially designed for this purpose.

Research continues to be performed to make the entire commercial nuclear industry more resistant to diversion of materials that could potentially be used for the production of nuclear weapons. This includes also the development of advanced techniques for the early detection of any violation of the Non-Proliferation Treaty.

Fast reactors with on-site recycling of the used fuel [4] (also referred to as 'integral fast reactors', IFR) could in the future make a major contribution towards reducing the risk of diversion of weapons-grade material for a number of reasons, including (a) no need for transportation of the used fuel outside the reactor site, (b) the plutonium and other actinides remain mixed in a form that cannot be used for nuclear weapons, and (c) strong reduction (or elimination) of the need for uranium enrichment facilities.

7. Wind and solar energy when applied to the electric grid

Wind energy has served humanity well during many centuries in many applications, including grinding wheat, pumping water and sawing wood. Large areas of low-lying wet land and lakes were made habitable and ready for agricultural use in previous centuries by removing the water by means of wind-driven pumps. Wind also served for a long time as an important energy source for transportation, making possible the exploration of the entire world by means of ships propelled by the wind. The important common characteristic of these applications is that they are not time-constrained: If there is no wind today, the tasks can be finished tomorrow or the ships will arrive somewhat later. This is, however, very different if one wishes to use wind and solar energy (that rely on capture of natural flows of diffuse kinetic and radiant sources) for base-load delivery of electrical energy to the grid because the grid imposes strict demands that have to be fulfilled instantaneously and completely.

Solar energy generated by means of photovoltaic (PV) panels have found important uses in special applications such as in space exploration and as small-power energy sources with built-in storage batteries for numerous applications (small light sources, calculators, parking ticket dispensers, watches). However, as an industrial-scale energy source for delivery of base-load quantities of energy to the electrical grid, solar energy will always be dependent on subsidies and special legally imposed regulations. On the other hand, wind energy is not likely to undergo a near-term revival of its traditional applications of grinding wheat, sawing wood and pumping water because modern technologies are more effective in this respect.

With the express purpose of reducing greenhouse gas emissions, many countries are promoting intermittent renewables by means of subsidies and by legislative directives requiring utilities to give priority access for delivery to the grid. A few countries have even announced that their target is to replace all (or most) of their existing generating capacity with renewables. Yet some of the energy sources that are termed 'renewable' are, in *certain* applications, not 'sustainable' because not all necessary criteria are being met.

For instance, as mentioned earlier, intermittent energy sources, *when used for delivery of base-load quantities of energy to the electric grid*, require the availability of flexible backup power plants (capable of rapid output adjustments) with capacity close to 100% of the nameplate capacity of the installed intermittent sources. This is because wind turbines and solar plants will vary their output between 0% and 100% of nameplate capacity and also because electrical energy from the grid is produced and consumed simultaneously and there can be no mismatch if grid stability and frequency is to be maintained within strict tolerances. Wind turbines deliver (over the course of a year) between about 20% and 40% of their nameplate production capacity (depending on location). Therefore, the backup power plants will have to deliver the remaining 60% to 80% of the energy (Fig. 1). This means that wind turbines would be more reasonably characterized as fuel-saving technologies for combustion power plants rather than stand-alone generators of electrical energy. Similar considerations are true for solar energy that has the added shortcoming of requiring the near-exclusive use of large land areas with more serious environmental consequences than wind installations (unless used at a

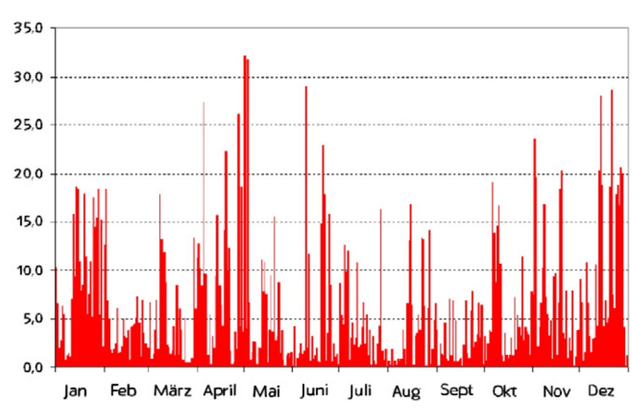


Fig. 1. Intermittency of wind energy in Germany. Annual share of daily wind power in respective daily peak demand in the E.ON-grid in Germany.
Source: UCTE Position Paper on Integrating wind power in the European power systems — prerequisites for successful and organic growth, May 2004.

Table 7
Seasonal variability of wind-generated electrical energy in Texas, U.S.A. highest and lowest monthly generation values (GWh).
Source: personal communication by Per Peterson.

Year	Highest value (month)	Lowest value (month)	Ratio Highest/lowest
2009	1993 (April)	1341 (July)	1.44
2010	2721 (April)	1589 (Sept)	1.75
2011	3311 (June)	1694 (Sept)	1.95
2012	3131 (March)	1821 (Aug.)	1.74
2013	3966 (May)	2023 (Sept)	1.96

smaller scale on rooftop installations). Some recent commercial solar thermal plants have included on-site heat storage for a few hours of output based on molten salts (at additional costs and involving larger mirror fields). However, this cannot compensate for large day-to-day and seasonal fluctuations in solar energy input (e.g. a string of cloudy days).

Seasonal variability is a major, yet rarely acknowledged, impediment to all-renewables scenarios (Table 7). Advocates often dismiss the issue of seasonal variability, pointing out that the wind blows more in the winter when solar output is minimal, and asserting that wind and solar balance out on a daily basis because wind blows more at night. However, these generalizations do not hold up to scrutiny. While some areas of the world do have more wind in the winter, others do not. In fact, it can be just the opposite in, e.g., California.

Until recently, California had more installed wind capacity than any other state in the U.S.A. Recent data (from 2013) reveal that the capacity factor of wind throughout California is slightly less than 25% over the year. But in the months of January, November and December of 2013, the capacity factor was about half that much. Meanwhile, the winter months in California saw solar photovoltaic output in the range of 11–12%. So even if utility-scale storage could be developed, wind and solar installations would have to be overbuilt by at least a factor of eight to provide the necessary capacity to power California. Barring that obviously impossible scenario, backup power generators will still be required, since there are strings of days when neither wind nor solar installations produce any meaningful output, especially in the winter.

The backup power for wind and solar plants depends in most cases on combustion of fossil fuels, primarily natural gas, because this is much less expensive than energy storage. Storage may be of various types: Thermal storage is practiced in heat-concentrating solar plants, potential storage is done by pumping up water or compressing air, whereas battery storage is a type of chemical storage. Most energy-storage facilities are not cost-effective at a large scale. However, in rare cases intermittent energy sources with stored-energy facilities may be economically viable, particularly for isolated locations without access to an electric grid [14].

The combination of grid-connected wind/solar installation plus gas-fired backup power plant will emit carbon dioxide and most likely also methane. Furthermore, grid-connected wind and solar installations will often be dependent on subsidies because redundant and under-utilized investments are required (i.e., for the intermittent source, the backup source and the additionally required transmission system). Because the output of wind-energy installations (averaged over a year), may have values from 20% to 40% of the name-plate capacity (depending on the location), the required investment for backup power is under-utilized by these same percentages. Many wind and solar installations are far removed from the load centers, requiring long-distance transmission lines, sized for their peak output, which are then under-utilized by 60% to 80%. Furthermore, the backup power plant will have to operate in stand-by mode, ready to adapt to the varying outputs (from 0% to 100%) of the intermittent energy source. This results in a penalty on the overall thermal efficiency of the backup plant. Taken in sum, this means that a combination of an intermittent energy source and its back-up power plant will seldom achieve economic viability (Table 8).

Much confusion exists concerning the generating cost per kWh for wind and solar plants. In this respect it is important to distinguish clearly between the 'bare' cost of a kWh generated by wind or solar installations that is consumed or stored locally and the cost of a kWh delivered to the electrical grid. In the latter case, it is necessary to account for the investments in the backup power and transmission capacity. The difference between these two prices can be substantial, the cost per kWh delivered to the grid being in most cases several hundred percent higher than the "bare" cost. As an example, Table 8 shows that for the combination of intermittent energy source plus gas-fired backup power, the cost for fuel per kWh varies between 5 and 12 times the cost for operation and maintenance.

Another consideration of importance is that the intermittency will cause grid disturbances that will deleteriously affect the grid's reliability, particularly if the installed capacity of the intermittent sources becomes a high percentage of the grid's total capacity. Delivery unreliability of the electrical grid can have serious economic and social consequences as was seen when long-lasting blackouts occurred in large urban areas. To date, in most grids, 'renewables' have only reached a low market penetration and so have been able to rely on existing marginal capacity, or large import–export capacity of interconnected other grids. Serious challenges will, however, emerge if there is a push to expand non-hydro renewables substantially within more traditional markets. In this connection, the question should be raised whether a country with a large installed wind/solar electrical generating capacity should pay for the use of the interconnected electric grids of neighboring countries for providing backup power capacity. This is of particular relevance for countries relying (or planning to rely) to a large extent on intermittent energy sources.

8. Methane as a greenhouse gas

As is well known, methane (CH_4, the principal molecular component of natural gas) is a potent greenhouse agent if released into the atmosphere [15]. This greenhouse-gas potency (also called 'global warming potential' or GWP) is defined as the ratio of the atmospheric heating effect of a discharge of methane over a certain time period (also referred to as 'time horizon') as a ratio of that of an equal gram-mole of carbon-dioxide (CO_2) over the same time period (Fig. 2, [16]). The half-life of methane in the atmosphere is about 11 years, meaning that the number of molecules in an emission of methane decreases exponentially to half

Table 8
Average power plant operating expenses for U.S. electric utilities (mills/kWh).
Source: U.S. Energy Information Administration http://www.eia.gov/electricity.

Year	Nuclear				Fossil (coal) steam				Hydro				Intermittent plus gas turbine			
	Operation	Maintenance	Fuel	Total	Operation	Maintenance	Fuel	Total	Operation	Maintenance	Fuel	Total	Operation	Maintenance	Fuel	Total
2008	9.9	6.2	5.3	21.5	3.7	3.6	28.4	35.7	5.8	3.9	0.0	9.7	3.8	2.7	64.2	70.7
2009	10.0	6.3	5.4	21.7	4.2	4.0	32.3	40.5	4.9	3.5	0.0	8.4	3.0	2.6	52.0	57.6
2010	10.5	6.8	6.7	24,0	4.0	4.0	27.7	35.7	5.3	3.8	0.0	9.1	2.8	2.7	43.2	48.7
2011	10.9	6.8	7.0	24.7	4.0	4.0	27.0	35.0	5.1	3.8	0.0	8.9	2.8	2.9	38.8	44.5
2012	11.6	6.8	7.1	25.5	3.7	4.0	24.0	31.7	6.7	4.6	0.0	11.3	2.5	2.7	30.5	35.7

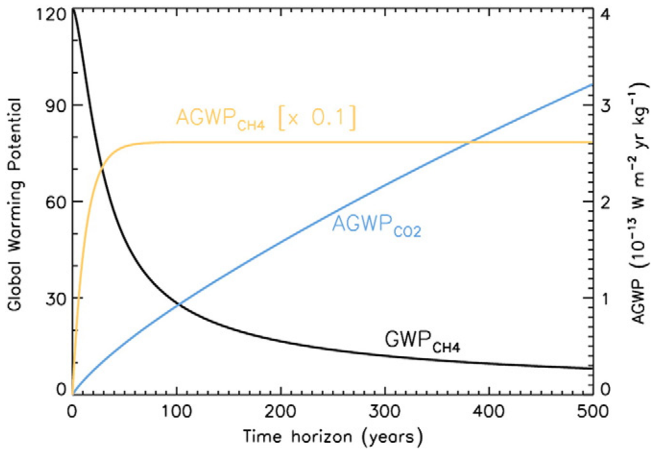


Fig. 2. Value of methane and carbon dioxide absolute global warming potential as a function of time horizon.
Taken from IPCC, Climate Change 2013, Chapter 8, p. 712).

its initial value in 11 years. Because the half-life of atmospheric methane is much shorter than that of CO_2, the ratio of their atmospheric heating effects depends on the time horizon considered: A short time horizon results in a higher value for the GWP than a long horizon. The Intergovernmental Panel on Climate Change (IPCC) determined that the values for the GWP of methane are about 60, 28, and 5, respectively, for time horizons of 20, 100 and 500 years [17]. The GWP value approaches 120 for the moment at which methane is released into the atmosphere, i.e. for a time horizon equal to zero.

The IPCC seems to recommend using a time horizon of 100 years. In reality, however, the large global combustion of natural gas does not occur in discrete discharges but takes place as a continuous flow. The associated leakage of methane into the atmosphere will therefore also occur incessantly and the amount of atmospheric methane will thus be constantly replenished. In fact, because of the worldwide rapidly increasing use of natural gas, the rate of replenishment exceeds the rate of decay, resulting in an ever increasing concentration of methane in the atmosphere. A time horizon of 100 years would therefore appear to be too long, particularly in view of warnings by IPCC of near-term impending dangerous climatic consequences due to global warming. A time horizon, considerably shorter than 100 years, would therefore seem to be more appropriate, e.g. 5 or 10 years.

Measurements and estimates of the leakage rates of natural gas into the atmosphere (at the mining well-head, during processing and from the long pipelines) vary considerably and have been reported to exceed 4% [18]. This may be expected if the gas is transported over large distances such as when coming from Siberia, North Africa and the Middle East.

Given that gas-fired stations produce about one half of the amount of CO_2 as that produced by coal-fired stations of equal generating capacity, it follows that:

- Gas-fired stations will have higher rates of greenhouse-gas emission than coal-fired stations of equal generating capacity if the atmospheric gas leakage rates exceed about 1.0% and 1.7%, respectively, for a GWP value of 100 (for a short time horizon) and for a GWP value of 60 (for a time horizon of 20 years).
- Grid-connected intermittent energy installations with gas-fired backup power, operating at 25% and 50% availability, will for GWP equal to 100 have a higher rate of greenhouse-gas emission than stand-alone coal-fired stations of equal generating capacity if the atmospheric gas leakage rate exceeds, respectively, 1.5% and 2.0% (*not taking into account the reduction in thermal efficiency of the backup power plant due to varying demand which could be as high as 20%*).
- Grid-connected intermittent energy installations with gas-fired backup power, operating at 25% and 50% availability, will for GWP equal to 60 have a higher rate of greenhouse-gas emission than stand-alone coal-fired stations of equal generating capacity if the associated atmospheric gas leakage rate exceeds, respectively, about 2.5% and about 3.35% (*not taking into account the reduction in thermal efficiency of the backup power plant due to varying demand which could be as high as 20%*).

Countries that depend on imported natural gas should be aware of the above and should take full responsibility for the associated atmospheric leakage of methane, including the part that occurs outside their borders.

It is important in this respect to consider that the current atmospheric concentrations of methane and CO_2 are, respectively, 1.893 ppm and 395 ppm, having risen since the start of the industrial revolution from, respectively, 0.722 ppm and 280 ppm (i.e., increases of, respectively 162% and 41%, indicating that the increase in methane concentration has been nearly four times larger than that of CO_2).

There does not exist a difference in the heating effect between methane molecules that were released recently into the atmosphere and those that were released a long time ago. Therefore, the currently present amounts of atmospheric methane and CO_2 contribute to atmospheric heating over the next 20 years in the ratio of, respectively, 95 to 395. For a time horizon of 5 years this ratio will be about 190 to 395, meaning that close to half of the atmospheric heating effect over the next 5 years is attributable to methane.

The atmospheric methane concentration of 0.722 ppm prior to the industrial revolution represents the equilibrium value between the rate of decay and the rate of replenishment by (mainly) non-anthropogenic sources (e.g. decaying vegetation, ruminant digestion). However, the current value of atmospheric methane concentration of 1.893 does not represent an equilibrium value because of the rapidly growing global role of natural gas as an energy source in the last half-century and the increasing release of methane from thawing permafrost. If the use of natural gas continues to rise rapidly (as is expected), it may well be possible that the warming effect of atmospheric methane will become comparable to that of CO_2 within a few decades. This would make it counterproductive to continue the large-scale use of natural gas as a fuel of primary importance and in particular to use it as the main fuel to provide the backup power for intermittent energy sources.

Nuclear and hydro are the only backup power energy sources that would result in an emission-free combination of intermittent plus backup energy source. However, the amount of hydro power is limited and is associated with serious environmental consequences. The use of nuclear power plants as backup for intermittent energy sources is not an economically viable option [19] and is arguably pointless from a climate-change mitigation perspective.

Using biomass for large-scale energy production is also a limited sustainable option. The reasons for this are multiple and include: (a) displacement of agricultural production, (b) land degradation after many years of intensive use through topsoil erosion and runoff with limited replenishment of stubble, (c) increased generation of anthropogenic methane, (d) dependence on shrinking freshwater resources, (e) land areas that can be withdrawn from food production for biomass production will decrease in time with the growth in the world population and (f) further destruction of natural habitats not yet under agricultural production. It should be noted that countries that import biofuels should take full responsibility for their part of the environmental impact caused in the country where the fuel is produced (including the associated greenhouse gas emissions).

9. Conclusion

Humanity will have to systematically reduce its dependence on the large-scale combustion of fossil fuels for energy production over the coming decades, with the aim of completing this transformation before the end of this century. In doing so, all energy sources may be considered and some will be deployed in useful 'niche' applications. However, only nuclear power plants are capable of sustainably and reliably supplying the large quantities of clean and economical energy needed to run industrial societies with minimal emission of greenhouse gases. Nuclear energy meets all the criteria of sustainability as defined by the U.N. Brundtland Commission [1].

In a first phase, the world's industrial nations should take the lead in transforming the major part of their stationary electrical energy generating capacity from fossil-fuel based to nuclear-fission based. With a long-term energy policy and proper incentives, this could be achieved within a few decades (as was already done by France). Such a transformation could drastically reduce the global rate of greenhouse-gas emission with respect to both atmospheric carbon-dioxide and methane.

Renewable energy sources (primarily wind and solar) will not be able to supply the needed large quantities of energy sustainably, economically and reliably. In addition, renewable energy sources with fossil-fired backup power will in many cases not contribute towards reduction of greenhouse-gas emissions. Distorting the market with subsidies and by legislation to attract intermittent energy technologies into applications for which they are not well suited is economically wasteful. Also, replacing stand-alone coal-fired stations with stand-alone gas-fired stations will, in many cases, not result in a reduction in the rate of emission of greenhouse gases due to (often poorly quantified) problems of methane leakage. Countries that depend on imported natural gas should be aware that they carry full responsibility for their part of the global consequences due to atmospheric leakage of methane associated with their part of the imported gas, including the leakage taking place outside their borders.

One solution to avoid 'free riding' would be a grid-connection fee, to be imposed on countries with a large intermittent generating capacity, for the purpose of compensating adjacent countries for the use of their interconnected electric grids as back-up power, and for having to accept surplus intermittent energy at times when it is not needed, thus forcing their base-load power plants to operate in an uneconomic 'accommodative' mode.

Intermittent energy sources with stored-energy facilities might, in some cases be economically viable, particularly for isolated locations without access to an electric grid. But the 'heavy lifting' in terms of replacing the global use of coal, oil and gas must come from a large-scale deployment of nuclear fission energy, with a goal for full fuel recycling for maximum long-term sustainability of this critical zero-carbon energy source.

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