Sustainability and Effectiveness of Low-Carbon Energy Sources;
the Roles of Critical Minerals and Natural Gas

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Summary.

This paper presents an evaluation of the two main types of presumably low-carbon energy sources, namely varying renewable energy (VRE, i.e., mainly wind and solar energy) and nuclear fission energy (NFE), concerning their sustainability and their effectiveness in reducing anthropogenic greenhouse gas (AGHG) emissions. Both VRE and NFE lay claim on being "inexhaustible" and "sustainable". However, VRE and NFE differ substantially in their material resource requirements, including that of critical minerals.

The conclusion of the study is that the effectiveness of VRE (if used for base-load electrical energy generation) in achieving a reduction in AGHG emissions is highly questionable (and possibly negative) and that large-scale deployment of VRE has a seriously deleterious environmental impact worldwide, resulting in a low sustainability grade. To the contrary, NFE has a high sustainability grade and is very effective in reducing AGHG emissions with a low environmental impact.

1. Varying Renewable Energy (VRE).

Numerous countries have replaced (or intend to replace) their electrical energy generating stations using fossil fuels with plants based on varying renewable energy (VRE; also called 'intermittent' renewable energy). The purpose is to combat global warming by reducing AGHG emissions (primarily carbon-dioxide - CO_2 - and methane - CH_4). However, VRE has a number of inherent deficiencies, namely:

(a) VRE varies between 0% and 100% of its installed ('nameplate') capacity because the wind does not always blow and the sun does not always shine (see Fig.1).

(b) VRE, if used for baseload electrical energy supply, needs to be backed up by other energy sources that have adequate capacity to be able to meet at all times the momentary demand of the electric grid. Backup energy sources can be based on either generated capacity (nearly always gas-fired turbines) or stored capacity. In the latter case, there are various options for storing energy, including pumped storage or storage in electrical energy accumulators (batteries).

(c) VRE plants produce, averaged over a time period of a year, only a fraction of their installed ('nameplate') capacity, which is referred to as their 'availability' or 'capacity factor'. The approximate values of availability are 15%, 20% and 40%, respectively, for solar panels, land-based wind turbines and sea-based wind turbines. *Because of these low availability values, the major part of the energy is produced, in most cases, by the backup generators, i.e., not by the VRE plants*.

(d) VRE is *not 'dispatchable'* , i.e., it cannot be called upon as needed to meet the changing momentary demand of the electric grid,

(e) VRE requires *priority access* to the electric grid for delivery (i.e., VRE plants deliver when/what is produced), thus placing other generators on the grid at a great disadvantage because they will have to accommodate both the rapidly changing output of the VRE plants and the changes in the grid's demand,
(f) VRE, if connected to the electric grid, requires major adaptations to the grid at high costs,
(g) VRE has as a major problem the fact that the *annual VRE production can be substantially different from year to year* (in many cases by a factor two or more). This means that the needed backup capacity has to be sized in accordance with the lowest expected VRE production, resulting in large under-utilized excess backup capacity with deleterious economic consequences.
(h) VRE plants require large amounts of materials (including critical minerals), if used for base-load electrical energy generation (see Table 1 and Fig. 2). In case VRE is to be backed up by stored energy capacity, various options exist, including pumped storage or storage in electrical accumulators (batteries). Apart from pumped storage (which requires the presence of a lake at elevation), most other storage options have limited capacity for base-load application (e.g., battery power for base-load application is limited to tens of MW, lasting only a short time, while requiring much space and a large quantity of materials (300 kWh / m3) and suffering serious energy conversion losses (70 -80%).

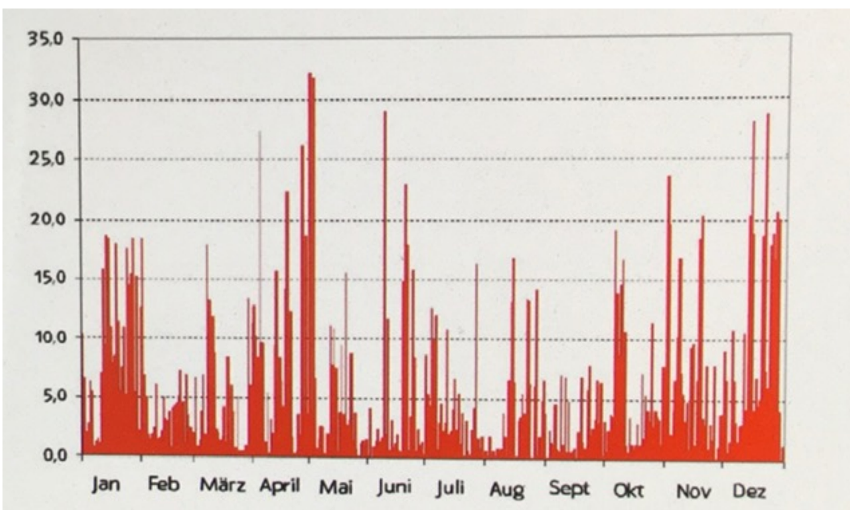


Fig. 1. An example of wind energy intermittency (E.ON grid in Germany).

1.2 The Role of Critical Materials in Varying Renewable Energy (VRE).

VRE, being a 'low-intensity' energy source, needs much space and many thousands of wind turbines and solar panels if used for base-load electrical energy supply. VRE plants contain large amounts of critical minerals (such as copper, nickel, manganese, cobalt, chromium, molybdenum, zinc, silicon. lithium and rare earths) that are produced by *extensive mining and processing operations requiring the operation of heavy machinery using fossil fuels*. The demand for critical minerals is expected to increase rapidly if large-scale deployment of VRE plants were to continue [1]. Furthermore, VRE plants (particularly wind turbines at sea that are continuously exposed to a severely corrosive environment), have a relatively short lifetime (about 15 years), thus requiring frequent replacement and often repair. Therefore, *these AGHG emissions will be continually recurring and will be substantial.* In view of this, it is of great importance that *the carbon footprint of the entire life cycle of VRE plants be determined over an extended period of time and be taken into account to determine the actual total emission.*

As shown in Table 1, VRE technologies require a considerably larger quantity of critical minerals per MW installed than other non-varying energy technologies.

Type of energy technology	kg/MW installed	kg/MW installed (corrected for availability)
Wind energy at sea	15,000	15,000*(100/40) = 37,500 (availability of 40%)
Wind energy on land	10,000	10,000*(100/20) = 50,000 (availability of 20%)
Solar energy	7,000	7,000*(100/15) = 46,700 (availability of 15%)
Nuclear fission energy	5,000	5,000*(100/90) = 5,600 (availability of 90%)
Coal combustion	3,000	3,000*(100/90) = 3,300 (availability of 90%)
Natural gas combustion	1,000	1,000*(100/90) = 1,100 (availability of 90%)

Table 1. Amounts of critical minerals needed for various energy technologies [1, 2]

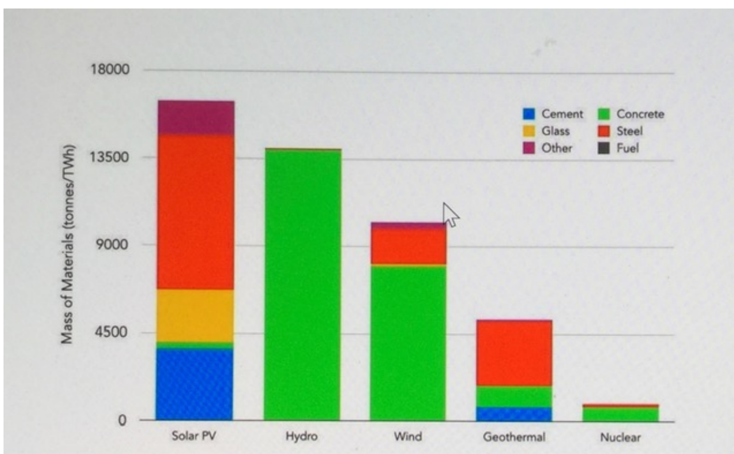


Fig. 2. Required materials for various energy technologies
(U.S.- DOE Quadrennial Technology Review, 2015)

Many countries import part (or all) of their wind turbines and solar panels. Because these countries are the end-users of these VRE plants and lay claim to the associated climate-related beneficial effect, they are fully responsible for the AGHG emissions associated with the entire fabrication process of the VRE plants, including the mining and processing of the needed critical minerals. In effect, by importing part (or all) of the VRE plants, these countries have 'outsourced' a large part of their AGHG emissions. Regrettably, *although AGHG does not know borders,* many countries prefer to disavow responsibility for the out-of-country AGHG emissions that they have caused, thus indulging in self-deception.

1.3 The Role of Natural Gas in Varying Renewable Energy (VRE).

Natural gas is often praised as being a “clean” fuel on the ground that its combustion produces about 50% less CO_2 than does the combustion of coal for the same amount of heat. However, methane (CH_4), the main component of natural gas, is a GHG that is much more potent than CO_2. In fact, the Intergovernmental Panel on Climate Change (IPCC) gives for the factor by which methane is more potent than CO_2 (referred to as the Global Warming Potential - GWP) the values 84 and 28, respectively, for time horizons of twenty years and hundred years [3]. Because of this GWP of methane the climate-related advantage of combustion of gas over coal is completely eliminated for l*eakage rates of the natural gas into the atmosphere of only 1.2% and 3.6%, respectively for time horizons of 20 years and 100 years.* Leakage rates of natural gas, measured at the well, often exceed these values with as consequence that the only advantage of gas combustion over coal is that it causes less air pollution.

Gas turbines that are run on natural gas, have two types of AGHG emissions, namely CO_2 (from combustion) and methane (from gas leakage into the atmosphere). *A relatively small leakage percentage of the natural gas will eliminate most (or all) of the climate-related beneficial effects of the* CO_2*-free energy produced by the VRE plants* [4, 5]. In the case that the natural gas is imported, it is essential to also take into account the out-of-country emissions of CO_2 and CH_4 at the well, during processing and during transportation. In case of transport by pipelines over long distances (such as, e.g., natural gas to Europe from Siberia and from the Sahara), these emissions are very substantial. *Many countries disavow responsibility for their out-of-border AGHG emissions associated with imported gas.*

Most gas turbines being used for VRE backup are of the combined-cycle type (commonly referred to as CCGT). This is because of their high thermal efficiency (about 60%). However, they lack flexibility, so that they are not well adapted to following the rapid changes in the VRE output. Single-cycle gas turbines (SCGTs) are better suited for following the VRE output, but have a considerably lower thermal efficiency of 40%. The lack of flexibility in CCGTs causes a substantial loss in thermal efficiency. Furthermore, in order for CCGTs to remain readily available in ‘stand-by’ condition, their power level cannot be reduced below a certain minimum level. This means that when VRE output is high, the CCGTs have often to be kept running at their minimum ‘stand-by’ power level, even though no CCGT output is needed. The consequence of these CCGT limitations is that *the combination of VRE together with backup CCGTs often has a higher AGHG emission than solely the CCGTs without VRE* [5, 6]. The reason is that the CCGTs without VRE do not suffer a loss in thermal efficiency because they do not have to follow the rapid changes in the VRE output, nor do they have to be kept running at the ‘standby’ power level. *Without VRE, the CCGTs will have to deal only with the daily slow and foreseeable changes in the demand of the electric grid*.

1.4 The Use of Hydrogen in Varying Renewable Energy (VRE).

In order to reduce the VRE dependence on natural gas, substantial investments are being made installing hydrogen-production plants that are to be run on VRE excess output. Operated under these conditions, these hydrogen plants will have a low production efficiency because of exposure to the rapidly varying VRE output. Also, this process will involve multiple energy conversions (electrical energy to hydrogen, then hydrogen back to electrical energy) each with a substantial loss. For that reason, *the production of hydrogen will not be sufficient to obviate the need for natural gas.* Furthermore, in order for the hydrogen to be available when needed, it has to be stored in high-pressure tanks that have to be well protected against external events and sabotage Also, the physical properties of hydrogen are sufficiently different from those of natural gas that mixed use or complete substitution may not be feasible. Hydrogen, being the smallest atom, is able to leak through many materials and may form hydrides with metals which causes embrittlement. The fact that pipelines for natural gas are not suitable for hydrogen will involve major costs. In conclusion, this proposed course of action will result in triple redundancy in capacity and investment as well as in triple under-utilization, rendering the economic viability very questionable.

1.5 Concomitant Problems with Varying Renewable Energy (VRE).

VRE development is in many countries supported by (direct and/or indirect) subsidies as well as by VRE-favoring regulations and mandates. However, the sad result of these recurring high expenditures is that electrical energy will be expensive and its delivery unreliable [4, 5]. The main reasons are the redundancy in investments (which is under-utilized) and the required very large costs associated with adapting the electric grid to VRE [7, 8]. It has often been said that the price of VRE plants has come down to the point that subsidies are no longer needed and that VRE competitivity has been achieved. However, this leaves out consideration of the fact that *VRE needs priority access to the grid, which constitutes a very large indirect financial support* because it places other generators on the grid at a great disadvantage. Furthermore, it usually also does not take into account the needed large investments in backup capacity and the costs incurred for adapting the electric grid to VRE.

A major concomitant problem is that large-scale development of VRE by industrial countries will require *extensive mining operations with a worldwide deleterious environmental impact (to a large extent in less-developed regions such as in Africa and Asia).* Other concomitant problems include visual/audial disturbance of local residents, environmental damage (including bird /bat kill), horizon 'pollution' and destruction of beautiful landscapes.

Because land-based wind turbines often have a production factor of only about 20% (as is the case in most West European countries), the combination of VRE plants together with CCGTs will often have a AGHG emission larger than that of CCGTs alone, as was explained earlier. However, notwithstanding the fact that land-based wind turbines offer little or no climate-related benefit, many "democratic" governments continue their policy of imposing these VRE installations (sometimes 200 m high) on protesting local residents, thus *depriving them of the enjoyment of their homes and lowering the value of their real estate property without offering financial compensation*.

1.6 Sustainability of Varying Renewable Energy (VRE).

The claim that VRE is sustainable and inexhaustible is based on the expectation that the wind will always blow and the sun will always shine. However, because VRE makes large demands on the earth's limited resources of critical minerals and natural gas, this claim is at best rather questionable.

2. <u>Nuclear Fission Energy (NFE)</u>.

Nuclear fission technology is a 'high-density' energy source, i.e., it needs little fuel and, if compared to VRE, it requires little space. Its carbon footprint is small, both inside-country and out-of-country and it has an availability of between 90% and 95%, delivering safe, *clean, reliable and dispatchable energy that is low-carbon and environmentally friendly at a price that is relatively stable over time, depending only for a few percent on the price of the fuel (uranium)* [9]. This is different for VRE plants where the price of the energy that is produced depends to a large extent on the price of natural gas that will, no doubt, increase substantially in the coming years. Furthermore, contrary to VRE plants that are affected by severe weather conditions (storms, freezing rain, hail, etc.) and that depend on the timely arrival of natural gas via pipelines*, nuclear power plants (NPPs) offer an energy system with a high level of security because the fuel for many months is already on-site in the reactor core and because they are designed and built to survive very severe weather conditions*.

2.1 The Role of Critical Materials in Nuclear Fission Energy (NFE).

As shown in Table 1 nuclear power plants require, for the same amount of energy produced, much lower amounts of critical materials than VRE technologies, namely by factors of about 7, 8 and 9, if compared with, respectively, wind turbines at sea, solar panels and wind turbines on land. New-built nuclear power plants have an expected life time of 90 years or more, so that their frequency of replacement will be smaller than that for VRE by a factor of about 6. Thus, *over a time period of about 90 years, the amount of critical minerals needed for nuclear power plants will be smaller than that for VRE plants by factors of about 42, 48 and 54*, respectively, for wind turbines at sea, solar panels and wind turbines on land. Moreover, the majority of the minerals needed for nuclear power plants do not belong to the rare species that require large mining and processing operations.

2.2 The Fuel Cycle of Nuclear Fission Energy (NFE).

The preferred fuel for nuclear power plants is the element uranium. It consists of two isotopes, namely U-235 and U-238 with abundances of, respectively, 0.72% and 99.28%. The current generation of commercial nuclear power plants use slow (also called “thermal”) neutrons and is able to fission only the U-235 atoms and a small fraction of the U-238 atoms. Most thermal reactors use light water as coolant and require the uranium fuel to be “enriched” in its percentage of U-235, leaving a substantial amount of uranium in which a large part of the U-235 has been removed (so-called “depleted uranium”). Thermal reactors, using heavy water as coolant, do not need enriched uranium. Nuclear reactors that use fast neutrons (also called fast reactors) are able to fission both isotopes of the element uranium.

An important aspect of NFE is the fuel cycle. For thermal reactors, the fuel cycle can be either “open” or “closed”. In both cases, the used fuel elements are temporarily safely stored above ground to “cool off”, i.e., lose most of their radioactivity. Subsequently, for the “open” case, the used fuel elements are disposed in deep underground tunnels (this practice is, among others, planned to be followed in Finland and Sweden). For the “closed” case, the fuel elements are, after a cooling off period, reprocessed, i.e., the fission products are chemically separated from the unused uranium in an aqueous chemical process operation. These separated fission products constitute the radioactive waste which is subsequently vitrified, to be later disposed in deep underground tunnels.

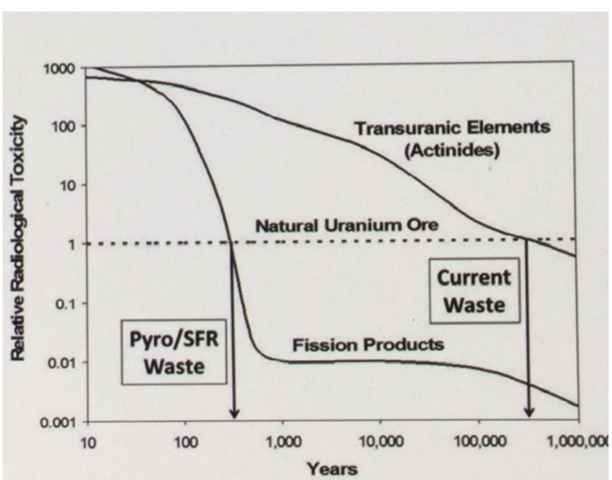
For fast neutron fission technology an “open” fuel cycle is not an option, mainly because the fissile content (or enrichment) of fast reactor fuel is considerably higher than that for thermal reactor fuel. *Recycling of used fuel elements has therefore to be an essential part of the fuel cycle of fast reactors*. While aqueous reprocessing of fast reactor fuel is feasible, it requires extreme safety measures for the prevention of unintended fission chain reactions which has deleterious economic effects. A non-aqueous method of fuel recycling, named “pyroprocessing”, has been developed and demonstrated at the Experimental Breeder Reactor EBR-II [10, 11]. Furthermore, a new process has been developed (called “electro-refining”) that is capable of separating the transuranic elements curium (Cm), plutonium (Pu), americium (Am), neptunium (Np) from the fission products. After removal, these transuranic elements can be recycled into fast reactor fuel to be “burned”(i.e., undergo transmutation) in the fast-spectrum neutron flux [10].

Table 2 indicates that the transmutation probabilities in a fast-spectrum flux make it possible to ‘burn” all transuranic elements. This is not possible in a thermal-spectrum neutron flux. Removal of all transuranic elements from the fission products has as consequence that the overall radiotoxicity of the “waste” (i.e., the remaining fission products) is reduced to a ‘historical’ time scale of about 300 years, as is determined by the fission product cesium-137 (Cs-137) having, among the remaining fission products, the longest half-life of 30.17 years. After 300 years (i.e., a time period approximately equal to ten times the half-life of Cs-137) the radiotoxicity of the fission products will be less than that of the uranium ore from which the uranium came. On the other hand, If the transuranic fission products are not removed, the waste will remain radioactive on a ‘geological’ time scale of more than 300,000 years (see Fig. 3). The anti-nuclear movement usually only mentions this latter long time scale, giving it as a reason for opposing nuclear energy. It seems that the information about the capability of reducing the radiotoxicity time scale of nuclear waste to 300 years is purposely not given wide dissemination.

An important advantage of reprocessing the used fuel is that the final volume of the remaining “waste” (i.e., fission products) is very much reduced and that the heat production declines much faster than that of the stored un-processed fuel elements. The heat load of stored un-reprocessed fuel elements is an issue that requires constant attention, placing limits on underground storage.

Isotope	Thermal Spectrum (%)	Fast Spectrum (%)
Np-237	3	27
Pu-238	7	70
Pu-239	63	85
Pu-240	1	55
Pu-241	75	87
Pu-242	1	53
Am-241	1	21
Am-242	75	94
Am-243	1	23
Cm-242	1	10
Cm-243	78	94
Cm-244	4	33

Table 2: Transmutation probabilities of transuranic elements [10, 11]



. Fig. 3 Radiotoxicity of remaining fission products [10, 11]

2.3 Industrial Applications of Nuclear Fission Energy (NFE)

NFE is a stable and reliable source of heat and electrical energy that can be used in many industrial processes as well as for space heating. Among the most useful applications is the production of hydrogen, that can be applied in many industrial processes, including production of steel and synfuels for transportation in areas where electrification is not economically viable (e.g., transportation by air). Fast reactors using liquid metals as coolant offer considerably higher temperatures than water cooled thermal reactors. Space heating (e.g., by means of special reactors) is another promising application.

2.4 Safety of Nuclear Fission Energy (NFE)

Nuclear fission technology is a safe source of energy, as is demonstrated by actual statistics, obtained over many years. This is amply demonstrated by data concerning fatalities in the various energy technologies (nuclear, coal, gas, hydro, wind, solar). As an example, Table 3 gives information for the U.S., pertaining to the period 2003 to 2012, expressed in energy produced per fatality. Surprisingly, wind/solar energy is not as safe as often is expected.

Nuclear	Coal	Gas	Hydro	Wind	Solar
7,900,000 GWh without a single fatality	140 GWh per fatality	51,800 GWh per fatality	463,200 GWh per fatality	21,600 GWh per fatality	2,500 GWh per fatality

Table 3. Energy delivered in the U.S. per fatality during the years 2003 – 2012 for various energy technologies based on actual statistical data. Nuclear energy was delivered in the U.S. during that time period without a single nuclear-related fatality (Source: Paul Scherer Institute, Switzerland).

During many years of commercial operation, few persons have died as a direct consequence of a nuclear-related event at a NPP. The accidents at Three Mile Islands and at Fukushima caused no deaths that were attributable to radiation over-exposure. However, the Chernobyl accident did cause fatalities due to radiation exposure. It should be noted the Chernobyl reactor was a plant with a special design that is no longer in use in current nuclear power plants.

For all three accidents, emergency evacuation did indirectly cause fatalities due to stress-induced trauma (mainly among elderly and sick persons). The tsunami of 2011 in Japan was a major natural disaster that affected a coastal stretch of about 2,000 km and that inundated more than 400 square km resulting in over 15,000 fatalities due to drowning and physical injuries. The evacuation in Japan (including areas not affected by radiation) is estimated to have caused about 2,000 fatalities.

Even when taking into account the deaths that occurred at Chernobyl and those due to evacuation, it is clear that nuclear fission has to be counted among the safest energy technologies. New-built reactors have further improved safety, among others, by incorporation of passive safety features which do not require active intervention but rely on inherent physical phenomena. A demonstration of inherent safety in a fast reactor, based on passive safety features, was given in April of 1986 at the Experimental Breeder Reactor EBR-II. Two tests (simulating “loss-of-flow” and “loss-of-heatsink”), both starting from 100% power, were performed while the reactor-protection system had purposely been put out of service. In both tests the reactor power level reduced to a safe self-cooling shut-down condition.

2.5 Future Development of Nuclear Fission Energy (NFE).

Thermal NPPs have been built (and are being built) on a commercial basis in many countries. At present (year 2021) some 440 NPPs are in operation with a combined capacity of 390 GWe, avoiding annually the emission of about 500 million metric ton of CO2. Additionally, about 55 thermal reactors are under construction and about 109 are being planned.

Significant progress continues to be made in the development of advanced reactors, including small modular reactors (SMRs) of a large variety with attractive design and operational features. SMRs, in addition to generation of electrical energy, may also be applied to supply heat for industry and for residential space heating. SMRs are expected to offer economic advantages associated with the fact that they are small enough to be mass-produced in factory and then transported to the site. When large generating capacities are needed, a number of SMRs can be built sequentially at the same site, thus offering the economic advantage that financing can be stretched out over time. Another attractive feature of SMRs is that they offer significant increased safety, resulting in a negligible radiation risk.

Although the R&D base of fast reactors is well in hand, fast reactors have up to now not yet been commercialized in the U.S., primarily because of *misinformed political opposition*. The Clinch River Breeder Reactor (CRBR) project was terminated and the EBR-II reactor was closed. However, once the need for fast reactors will have been recognized, large-scale commercialization can be achieved within a relatively short time period (ten years or less). *In this connection, it is of interest to note that the first nuclear fission reactor, producing a substantial amount of electrical energy, was a small fast reactor named the Experimental Breeder Reactor EBR-I (December 1951).*

Other countries, including Russia, India and China have continued work in this important area. Russia has been operating BN-600 since 1980 and completed a larger BN-800, which started commercial operation in 2016. In addition, a test reactor MBIR and a lead-cooled fast reactor BREST-300 are under construction in Russia. India has been operating its Fast Breeder Test Reactor since 1985 and a commercial prototype 500 MWe PFBR is expected to start up this year. China has operated the China Experimental Fast Reactor since 2011 and started construction of the commercial China Fast Reactor-600 Unit 1 in 2017 and Unit-2 in 2020.

Superphénix (1,240 MMe) was a European international reactor project in France, aimed at the commercialization of fast reactors, as is described in the book 'Pourquoi Superphénix" by the well-known French scientist/engineer Georges Vendryes [12]. Unfortunately, after completion, it had to be closed in 1998 at the insistence of the 'green' movement in France ("les Verts").

Notwithstanding the foregoing which shows the important role that nuclear energy can (and should) have in combatting climate change, many industrial countries (particularly in West Europe) are phasing out their nuclear power plants or have passed laws to do so at a future time. This is a highly regrettable course of action because, *not only are these countries endangering their own economic future while not achieving their climate objectives, but by continuing to deploy VRE on a large scale, they will also be making a preemptive large claim on the global resources of critical materials to the detriment of industrially less-developed countries.*

2.6 Sustainability of Nuclear Fission Energy (NFE).

The claim that nuclear-fission technology constitutes an inexhaustible energy source is based on the fact that fast reactors are able to fission both isotopes of the element uranium and *are therefore able to harvest about hundred times more energy from the same amount of uranium than thermal reactors*.

The reasonably assured resource of uranium that can commercially be mined is estimated to be about 5,600,000 tonnes. At the current consumption rate of about 75,000 tonnes per year, this will suffice for about 75 years if used in thermal reactors. No doubt, additional uranium resources will be discovered. If used in fast reactors, the resource of uranium, combined with the uranium of used fuel elements from thermal reactors and the accumulated large amount of depleted uranium, will suffice for thousands of years. Furthermore, because the amount of uranium used by fast reactors is very small, *the resource base of uranium that can be exploited in a commercially viable way, is very much larger for fast reactors than for thermal reactors*. In fact, uranium, if used in fast reactors, could commercially be harvested from very poor uranium ore deposits and from the oceans. Furthermore, if the uranium supply were ever to become depleted (which is highly unlikely), then the element thorium could take its place. This makes *fast nuclear fission technology truly an inexhaustible energy source* [10], as was first foreseen by the well-known Italian-American physicist Enrico Fermi in the late 1940s. It was under his leadership that the feasibility of a self-sustaining controlled nuclear fission chain reaction was first demonstrated on December 2, 1942 at the University of Chicago.

<u>Conclusions:.</u>

1. VRE plants have a low sustainability grade and a large carbon footprint. This is attributable to their need for large quantities of critical minerals and natural gas.
2. NFE plants have a high sustainability grade and a small carbon footprint. This is attributable to their small requirement of critical minerals, as well as to the fact that they offer an inexhaustible energy source with low demand for fuel.
3. In order to obtain the true carbon footprint of a country, it is necessary to include the in-country emissions as well as the out-of-country emissions of AGHG
4. The carbon footprint of most countries will be found to have only minimally decreased (or not at all) by deployment of VRE plants if all associated AGHG emissions are properly taken into account. Hydrogen production plants to be run on excess VRE, will not change this outcome.
5. Countries that seriously intend to reduce their carbon footprint and wish to strive for sustainability in their energy supply, should stop phasing out nuclear power plants and should start building new ones. Such a policy requires a long-term vision and the willingness to assign proper value to reliability and security of energy availability.

<u>References.</u>

1. OECD - International Energy Agency (IEA): ‘the Role of Critical Minerals in Clean Energy Transitions’, Report , 2021.
2. Alfred Voss, ‘Energy and Sustainability – An Outlook’,
   Paper, International Materials Forum, Bayreuth, 2006.
3. Intergovernmental Panel on Climate Change (IPCC): Report AR6, 2021.
4. Barry W. Brook, et al., ‘Why Nuclear Energy is Sustainable and has to be Part of the Energy Mix’, Elsevier Magazine Sustainable Materials and Technologies, vol. 1-2, pages 8-16, Dec. 2014.
5. Agustin Alonso, et al.: ‘Evaluation of the Effectiveness and Economics of Varying Renewable Energy as a Means for Abating Global Warming’,
   Jaderna Energie, April / May 2021 (Czech Republic).
6. Alfred Voss: ‘Can the Objectives of the “Energie Wende” be Achieved?’,
   Paper, Tenth International School on Nuclear Power, Warsaw, November 27, 28, 2018.

7. Alfred Voss, Benjamin Fleischer: 'System Cost of Low-Carbon Electricity – A German Case Study, emphasizing the Effect on Transport and Distribution Grids',
   Paper, OECD-NEA Workshop, September 22, 2016.
8. Jan-Horst Keppler: 'The Cost of Decarbonization', OECD-NEA report, 2018.
9. Jozef Misak: 'Essential Role of Nuclear Power for Implementation of the Conclusions of the Climate Conference 2015',
   Paper, IAEA Technical Meeting TM-52285, Amsterdam, Netherlands, June21-23,1016.
10. Charles E. Till and Yoon I. Chang: 'Plentiful Energy; the Story of the Integral Fast Reactor',
    Book CreateSpace 2011, ISBN 978-1466384606,
11. Yoon I. Chang, et al.: 'Conceptual Design of a Pilot-Scale Pyroprocessing Facility',
    Nuclear Technology, Volume 205, 708 – 725, May 2019
    (DOI: https//doi.org/10.1080/00295450.20181513243)
12. Georges Vendryes: 'Pourquoi SuperPhénix', book 1997.
13. Yuzhong Zhang, et al.: 'Quantifying methane emissions from the largest oil-producing basin in the United States from space', American Association for the Advancement of Science.

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