Evaluation of the Effectiveness and Economics of Varying Renewable Energy as a Means for Abating Global Warming

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Summary:

Humanity has arrived at a critical point in history, requiring major decisions that will have long-term, global consequences. Among the topics requiring urgent attention are global warming and the availability of a sustainable food and energy supply for all of humanity. This study is primarily intended to evaluate the energy-related aspects of global warming, but addresses indirectly also sustainable energy supply. Feasible options for abatement of global warming appear to be already available, but a unified policy is currently lacking because political action groups advocate different approaches. While energy from nuclear fission has proved to be an effective means for reducing atmospheric emissions of anthropogenic greenhouse gas (AGHG), its use is vigorously opposed by socio-political groups that advocate heavy reliance on varying renewable energy (VRE) sources (mainly wind and solar plants, backed up by gas turbines).This study is intended to contribute to this subject by evaluating the contribution that VRE might be able to make towards abatement of climate change, as well as the associated economics.

In summary, the main conclusions that were reached are (a) the climate-related beneficial effect of the CO_2*-free energy produced by VRE plants will be reduced or eliminated by the loss in thermal efficiency of the backup generators due to the rapidly changing load requiring high ramp rates, and the lack of flexibility of combined-cycle gas turbines, (b) leakage into the atmosphere of natural gas used by backup gas turbines will reduce or eliminate the beneficial effect of* CO_2*-free energy produced by VRE plants, based on the IPCC values for the global warming potential (GWP) of atmospheric methane, (c) VRE plants are not likely to be economically viable without subsidies and favoring (positively-biased) regulations, (d) higher percentages of VRE on the electric grid will result in disproportionately higher kWh costs*, (e) *grid-connected VRE plants have the general effect of reducing grid reliability, which will have deleterious social and economic consequences, (f) the presence of VRE plants on the electric grid excludes the possibility of a level playing field for other generators on the grid.*

A conclusion, unrelated to VRE, is that replacing coal-fired stations by gas-fired stations will not result in a climate-related beneficial effect if the leakage into the atmosphere of used natural gas exceeds about 4% (based on IPCC values of GWP for atmospheric methane).

Introduction:

Renewable energy, such as from wind and falling water, have served humanity well during millennia for tasks that are not time-constrained, such as pumping water, sawing wood, weaving cloth and transport by sailing ships. Modern forms of varying renewable energy (VRE) sources (mainly wind turbines and solar panels) continue to be useful in many applications which lack access to the electrical grid. However, if VRE sources (also called 'intermittent' renewables) are connected to the electrical grid, they must contribute to tasks that are time-constrained, for which they are not well suited and for which they require the assistance of backup generating capacity in order to be able to meet the grid's demand. Notwithstanding this limiting characteristic, VRE sources are viewed by many as effective means for reducing AGHG emissions. The purpose of this study is to examine and critique the effectiveness of VRE plants in reducing CO_2 emissions, as well as the associated economics.

Many governments have promoted the construction of VRE plants deployed for delivery of energy to the electric grid. This was mostly done by means of subsidies and highly favorable (positively biased) regulations, in part to meet international commitments concerning the reduction of AGHG emissions. However, VRE sources have two major disadvantages, namely (1) their output varies often and widely and (2) they have a low energy 'density', requiring considerable space for deployment and large amounts of construction materials. Moreover, VRE sources, if connected to the electric grid, have eight additional disadvantages: (3) they require flexible backup generating capacity, (4) they are not 'dispatchable', i.e. their output cannot be controlled to meet the grid's changing demand, (5) they require priority access to the grid for delivery of energy, (6) their annual output varies considerably from year to year, requiring much additional under-utilized backup capacity, (7) they necessitate major high-cost adaptations to the electric grid at higher market penetrations, (8) they have a strongly deleterious effect on the reliability of the electric grid, (9) they are vulnerable to severe weather conditions and (10) they need substantial quantities of materials of great scarcity (including rare-earths), requiring large quantities of fossil energy to produce.

Advocates of VRE point to the fact that wind / solar energy has two attractive characteristics, namely (a) it is cost-free and (b) it does not produce CO_2. This may be true in some cases; however, it is not valid for VRE plants connected to the grid, because in that case the energy delivered has to meet a number of strict criteria, including stability of voltage and frequency, as well as reliability of delivery. To meet these criteria and to keep the electric grid in balance, it is necessary that the VRE plants are backed up to close of their maximum design (also called "nameplate") capacity by means of flexible generators. *In short, grid-connected VRE sources and their backup generating sources are bound together like Siamese twins*. Consequently, energy from a VRE source and its backup that is delivered to the grid, cannot be considered to be CO_2 emission free. Furthermore, the cost of the kWh delivered to the grid by VRE and its backup, is considerably higher than the 'bare' cost (often by a factor as high as 3). The latter is defined as the kWh cost delivered by the VRE source to the grid without accounting for the costs associated with the backup generators and/or storage facility, as well as the cost of needed adaptation and enlargement of the transmission system. This 'bare' cost is only pertinent for isolated sites that do not have a connection to the grid such as when VRE is used to charge a local energy-storage facility. Nevertheless, advocates of grid-connected VRE often mention 'bare' costs, even though this is not relevant for the kWh price delivered via the grid to the consumer.

Although atmospheric and climatic conditions differ widely around the world, the study presented in the following sections, and the conclusions reached within, will be, in general, pertinent to most regions.

Effectiveness of VRE Plants Concerning Reduction of Anthropogenic CO_2 Emissions

Land-based wind turbines in many regions of the world (including Western Europe) typically have an annual production factor of about 20%, meaning that they produce, averaged over a year, only about 20% of what they could produce if the wind would constantly blow at optimal speed. Because the wind velocity varies widely and may at times be zero, these wind turbines have to be backed up by a flexible generating capacity approximately equal to the name-plate capacity of the wind turbines. Thus, the energy produced by the wind turbines (averaged over a year) will need to be complemented for about 80% by the backup generators.

Open-cycle gas turbines (OCGTs) are flexible and thus well-suited to complement the rapidly varying output of wind turbines. They have a thermal efficiency at normal load of between 35 and 42%, but will suffer a reduction in thermal efficiency (20%) when having to compensate for the rapidly changing output of the wind turbines. Combined-cycle gas turbines (CCGTs) are lacking in flexibility and are therefore not well-suited to serve as backup. They have a combined overall thermal efficiency of up to 62% but will suffer a reduction in thermal efficiency of at least 20% if called upon to complement the rapidly changing output of the wind turbines. This loss may be considerably higher for large upward swings in wind energy, because the CCGT power cannot be reduced below a certain level in order to remain readily available in stand-by mode. Under those circumstances, the CCGTs will continue to operate at their minimum power level even though the electric grid does not call for it.

The flexible backup-generating capacity for wind /solar plants is best provided by a mixture of OGGTs and CCGTs. Because of the more than 20% difference in thermal efficiency between OCGTs and CCGTs, as well as the fact that CCGTs are very limited in their capability to follow rapid and large changes in wind velocity, the result is that grid-connected land-based wind turbines with backup by gas turbines have, in many cases, CO_2 emissions that are higher (or only slightly lower) than CCGTs without any wind turbines. In the latter case, OCGTs will not be not needed and the CCGTS do not have to deal with the rapid changes in VRE output but only with the known diurnal slower changes in grid demand.

For offshore wind turbines, the production factor is about 40%. The loss in thermal efficiency of the backup gas turbines will be similar to that for land-based wind turbines, meaning that grid-connected offshore wind turbines with backup by gas turbines will have, in many cases, CO_2 emissions that are only about 20% lower than for the case of solely CCGTs without any wind turbines.

When calculating the total balance of CO_2 emissions it is important to include the large amount of fossil fuel that is required for the construction and replacement of the VRE installations. This is of particular importance for offshore wind parks, that require specialized mountings and are exposed to a severely corrosive environment, necessitating frequent replacement.

The CO_2 accounting should also include the considerable amount of fossil fuel that is required for the production, processing, compression and transportation-related pumping of the natural gas. This is of particular importance for natural gas transported over large distances.

Advocates of VRE are inclined to omit this, claiming that CO_2 emissions outside a country are not the country's responsibility. But that is clearly incorrect accounting. In reality, the end-user of natural gas is clearly co-responsible for all the gas-related CO_2 emissions in proportion to the quantity of gas that is used.

For solar installations, the production factor in most locations is at most 20%. Therefore, the result will be similar to that of land-based wind turbines, namely that grid-connected solar installations with backup by gas turbines have, in many cases, CO_2 emissions that are higher (or only slightly lower), than that of solely CCGTs without any solar panels.

Some countries (and/or regions), instead of providing themselves with adequate backup capacity for their VRE plants, find it preferable to use the electric grids of adjacent countries (and/or regions) as their backup generating capacity. This is done by importing part (or all) of the needed backup electric energy from sources outside their service area. Under such circumstances, unless the imported electric energy is derived from non-carbon sources (e.g., hydro or nuclear), it would be misleading to claim VRE effectiveness in reducing CO_2 emission within the pertinent service area. Furthermore, this situation may lead to loss in reliability of the electric grids in the adjacent countries and/or regions.

Global Warming Potential of Anthropogenic Methane in the Atmosphere

Methane (CH_4) in the atmosphere is, according to the Intergovernmental Panel on Climate Change (IPCC), considerably more potent than CO_2 as a GHG. In order to indicate the strength of the climate-related impact of GHGs other than CO_2, the IPCC makes use of the concept of global warming potential (GWP), often also called '*CO_2-equivalent emission*'. The GWP of a GHG is defined as the ratio of the climate-related impact of a pulse of the GHG and the impact of an equally large pulse of CO_2, integrated over a certain time frame (referred to as 'time horizon'). Notwithstanding the fact that IPCC indicates that there exists a considerable degree of uncertainty in the values of the GWP, it has become the default metric for transferring emissions of different GHGs to a common scale.

Because the decay half-life of methane in the atmosphere (12.4 years) is much shorter than that of CO_2, the effect of a pulse of methane released into the atmosphere will decrease faster with time than a pulse of CO_2. The IPCC gives for the GWP of atmospheric methane the values 120, 84 and 28 for time horizons of, respectively, 0, 20 and 100 years (see Table 8.7 in IPCC report AR5 [1]).

About 60% of the total flow of methane being emitted annually into the atmosphere is of anthropogenic origin. Among the main sources of this atmospheric anthropogenic methane are leakage of natural gas produced by drilling, agriculture and livestock. The main component of natural gas is methane. The leakage of natural gas takes place at the production wells and during processing, compression and transport, as well as at the site of the end-user. Methane is also emitted from coal mines. The fact that the methane concentration in the atmosphere continues to increase indicates that its emission rate into the atmosphere exceeds the decay rate of the methane that is already present.

The importance of anthropogenic methane in the atmosphere becomes apparent by comparing the climate-related impacts of the current atmospheric concentrations of CH_4 and CO_2, which are, respectively 1.854 ppm and 407 ppm. On the basis of the IPCC recommended value of 120 for GWP (i.e., at time-horizon zero), one finds that CH_4 and CO_2 are contributing (1.854 * 120) / {(1.854 * 120) + (407 * 1)} = **35%** and (407 * 1)/ {(1.854 * 120) + (407 * 1)} = **65%**, respectively, of their combined global warming effect. Note that these percentages are *independent of a time horizon*, because they are based on the currently existing (instantaneous) concentration values. Note also that the atmospheric concentration of CH_4 has increased about four times faster than that of CO_2 since the beginning of the industrial revolution. In view of the ongoing thawing in permafrost regions (Russia-Siberia, U.S.A.-Alaska, Canada), it is likely that the methane concentration in the atmosphere will start rising more rapidly in coming decades.

The natural gas that is leaked into the atmosphere in connection with the operation of the backup gas turbines will have a negative climate-related impact that will reduce or eliminate the beneficial effect of the VRE-related reduction in CO_2 emissions. Averaged over a year, the energy produced by the combination of land-based VRE (wind parks and solar installations) and the backup gas turbines will be about 20% CO_2-free (not taking into account the loss in thermal efficiency of the gas turbines due to the changing VRE output). The percentage value of the methane leakage rate that will eliminate the beneficial effect of land-based VRE plants (i.e., the CO_2 equivalence of the leaked methane is equal to the CO_2 emission that was prevented by the VRE) will be proportional to 20/28 for a time horizon of 100 years for which GWP equals 28. As a percentage of the gas combustion rate this is about (20/28)/80 = **0.89%.** Note that the value of the thermal efficiency of the gas turbines does not enter in the above calculation because the same value will appear in both numerator and denominator. Similarly, for offshore wind parks with production factors of 40%, the value of the methane leakage rate that will eliminate the benefits of the VRE plants is about (40/28)/60) = **2.4%** for a time horizon of 100 years. Note that the time horizon of 100 years was chosen because it represents about 8 times the decay half-life of methane, meaning that most (99.6%) of the methane that was released at time zero will have decayed by then. In this way the full integrated effect of a pulse of methane (released at time zero) over the 100-year period is being considered. For a time horizon of 20 years, over which GWP equals 84, the methane leakage rate that will eliminate the beneficial effect of VRE plants will be about (20/84)/80 = **0.30%** and about (40/84)/ 60 = **0.79%**, respectively for land-based and sea-based plants. Note that the leakage values for the 20-year horizon are smaller than those for the 100-year horizon, because the effect of the methane leaked at time zero had not decayed as much over 20 years as over 100 years (67.3% of the methane has decayed after two decades).

Some countries are taking climate-related credit for having switched part of their electricity generation from burning coal to burning natural gas. This argument rests on the grounds that burning natural gas produces about half the quantity of CO_2 compared to burning coal for the same amount of heat. However, this benefit of burning natural gas over burning coal will be eliminated if the gas leakage rate into the atmosphere exceeds a value of about (50/28)/50 = **3.6%** for a time horizon of 100 years (not taking into account natural gas released from coal mines). For a horizon of 20 years, the leakage rate that would result in equivalence of CO_2 emission would be about (50/84)/50 = **1.2**%

Leakage values for natural gas that are considerably higher than 4% may be found in the open literature. This leakage is of particular relevance for gas transported over long distances, such as gas from Siberia to Western Europe (4500 km). A recent study reports gas leakage rates of 3.7% at the production wells in North Dakota, U.S.A [2].

Economic Viability of VRE Plants

The fact that VRE plants can only function with priority access to the grid, implies the imposition of a 'master/slave' relationship on the backup generators that are being forced to function as 'slave' to the needs of VRE. The backup generators will thus have to operate under *highly disadvantaged* conditions because they have to continuously accommodate the rapidly changing VRE output as well as the changing demand of the grid, while the VRE plants are permitted to continuously deliver to the grid whatever they produce and what the grid can accept. In this situation the *concept of a 'level playing field' for the VRE backup generators clearly cannot exist.*

The combination of VRE plants backed up by gas turbines and/or energy storage facilities, has two major aspects that detract from economic viability, namely (1) redundancy of investment, (2) under-utilization of available capacity. This is true for generating and/or storage capacity as well as for transmission capacity.

The fraction of the generation capacity of the VRE plants that remains unutilized (averaged over a year) is about 80%, 60% and 80% of the nameplate value, and the capacity of the backup gas turbines that remains unutilized is about 20%, 40% and 20%, respectively for land-based wind parks, offshore wind parks and solar installations. These are approximate values because the VRE production factor (expressed as percentage of nameplate capacity) may not in all cases equal the percentage of energy produced, in particular when VRE nameplate capacity exceeds the available backup capacity. This latter situation is, however, highly undesirable because, when VRE goes to zero (wind still, no sun) , there would be insufficient backup capacity to keep the electric grid in balance which could lead to grid collapse.

The fraction of the VRE associated transmission capacity that remains unutilized (averaged over a year) is about 80%, 60% and 80%, respectively for land-based wind parks, offshore wind parks and solar installations. Because the cost of VRE-related adaptation of the electrical grid is very high, this low utilization constitutes a heavy cost penalty, in particular for offshore wind parks that may be far removed from the load centers [3].

It is important to point out that for increasing percentages of VRE connected to the grid, the associated cost penalties due to redundancies in both generation and transmission capacities, will increase substantially and disproportionally [4, 5].

Furthermore, VRE sources have a deleterious effect on the reliability of the electric grid, thus increasing the probability of disruptions in delivery, including long blackouts with serious economic and social consequences. Even minor disruptions can have deleterious consequences for industry, hospitals, data centers, etc. [6].

In view of the large redundancy in investment and the low utilization of the VRE plants, the backup gas turbines and the associated transmission systems, it is concluded that grid-connected VRE sources are not likely to be economically viable notwithstanding the fact that they start out with a large inherent advantage, as noted earlier. The possibility of economic viability is further diminished by the fact that *the annual production of VRE sources varies widely from year to year* (often by a factor two or more), necessitating additional under-utilized backup capacity.

Only by distorting the energy market by means of (direct and indirect) subsidies and favorable (positively biased) regulations, is it possible to create the impression that VRE delivered to the grid, can be competitive. Another way to distort the market is by 'shifting' VRE-related expenditures, such as by writing off the costs for adaptation of the electrical grid separately as "infrastructure improvements". This is unjustified because these costs are clearly solely linked to VRE. Such bookkeeping practices may be politically expedient, but will only obfuscate decision making and will have long-term deleterious economic consequences.

It has been stated that the solution to the inherent shortcomings of VRE is the application of energy storage which would then be expected to 'level out' the VRE source's rapidly varying output. Such energy storage could be based on various types of energy, including electro-chemical (e.g., battery power packs), potential (e.g., elevated water reservoirs, hydro power) and kinetic (e.g., large flywheels). However, the rapidly and widely changing large amounts of energy on the electric grid would necessitate, in most cases, very large investments that would remain under-utilized. It is also important to note that conversions between different energy types is not without substantial losses. As an example, storage of VRE if based on elevated water reservoirs (e.g., artificial lakes), involves two energy conversions with a combined loss that could well exceed 30%. It is for these reasons that only hydro power (where available) is considered economically viable. Hydro power has the fortunate characteristic of being an energy source with 'built-in' storage capacity (this is only true to a much lesser extent for run-of-the-river hydro power which is the form preferred by environmentalists).

Notwithstanding the fact that there exists no compelling economic incentive for installing grid-connected VRE plants with a combined nameplate capacity that exceeds the maximum demand of the grid, some countries or regions have done so anyway. This further contributes to the deterioration of grid reliability. In fact, some countries that are exposed to sudden large bursts of excess VRE coming from an adjacent country (e.g. due to strong wind gusts), have indicated the need to protect their grid reliability by installing the capability of temporarily cutting external grid connections to their service area. Some countries have already done so (including the Czech Republic) by installing the needed equipment at high costs. A question that may well be raised in this connection is whether country or region 'A' that knowingly is causing damage in country or region 'B', owes offsetting payments to country or region 'B' in compensation for the damage done and/or the costs incurred for prevention of damage.

Discussion:

Much confusion and misleading information exists regarding VRE on the electric grid. Most of this is due to incomplete and biased reporting. E.g., proponents of VRE often state that a specific VRE park will deliver enough energy for a specified high number of households. This is misleading advertising practice because usually no mention is made of the fact that the backup gas turbines are producing the major part of the energy. In fact, without backup gas turbines, the households would be sitting in the dark for much of the time. Furthermore, VRE proponents will often imply to have an emission-free generating capacity equal to that of the nameplates of the wind turbines. However, it usually is not mentioned that the actually produced CO_2-emission-free energy is only a small fraction of the installed nameplate capacity. Furthermore, most likely no mention is made of the fact that this emission-free component is, to a large extent (or fully), eliminated by the increased use of fuel by the backup gas turbines due to the loss in thermal efficiency and the limited flexibility of CCGTs, as well as due to leakage into the atmosphere of natural gas.

Given the low production factors of land-based wind turbines in many countries (including Western Europe), one may well wonder why it was deemed socially and economically justified to install them, notwithstanding the fact that nuclear energy offers a much more effective means to reduce CO_2 emission. This matter becomes even more questionable in view of the disappointing fact is that the actual VRE-related reduction in CO_2 emission is rather small or even negative**.** It is therefore truly deplorable that these very costly construction programs of land-based wind turbines were forced on the affected population, often against strong local opposition, including complaints about visual-horizon pollution, killing of protected birds and bats and noise / light disturbance. Similar considerations are valid for offshore wind turbines where the attained reduction in CO_2 emission is low or non-existent and the cost of construction and maintenance is very high. Moreover, the construction and maintenance of off-shore wind turbines is not without danger for the work crews and may well result in numerous human fatalities.

Countries wishing to substantially reduce or eliminate anthropogenic CO_2 emissions are not likely able to do so without nuclear energy [7, 8, 9,10, 11]. Excluding nuclear energy implies either continued large-scale dependence on the combustion of fossil fuels, entailing long-term deleterious climatic consequences, or, if relying heavily on VRE, long-term irreparable economic damage with serious social and health consequences. The only exception to this may be for countries with a large hydropower capacity and/or an energy storage capacity that is economically viable.

Some countries and organizations seem to have come to the conclusion that a ‘symbiotic’ coexistence between VRE and nuclear energy is possible and desirable [12]. In this connection, some persons have stated that “nuclear energy is the ‘enabler’ of large-scale deployment of VRE”. They seem to propose using nuclear power plants for VRE backup instead of backup by gas turbines. However, the term ‘symbiosis’ implies a mutually beneficially relationship which in this case is not valid because there is nothing ‘symbiotic’ about an arrangement, in which nuclear energy is forced into the disadvantaged position of serving as ‘slave’ for VRE. This disadvantage would be the similar for any other backup dispatchable energy source with the exception of hydro power. Nuclear power plants are, however, more disadvantaged to function as backup to VRE than gas turbines because the nuclear kWh cost is determined by high upfront capital and investment cost and very low fuel cost, whereas the kWh produced by gas turbines is characterized by relatively low initial investment and relatively high fuel cost. Furthermore, if nuclear power plants are available to serve as backup for VRE, why then not dispense completely with the VRE and just keep the nuclear energy? It would be very effective as regards GHG reduction and would be less complicated and much less costly.

It is of great importance to consider that VRE sources are highly vulnerable to extreme weather conditions (severe storms, hail, freezing rain, etc.). The occurrence of an event that would deprive a large group of people for a long time of its needed electrical energy supply, has a probability that is considerably higher for VRE than for nuclear energy. The reason is that VRE plants are without protection against extreme weather, being highly exposed and spread out over a large area. Nuclear power plants occupy a small area and are well protected, having been designed to withstand severe external events.

Why did (and do) so many industrially developed countries spend so much effort and financial resources on these ineffective and costly VRE construction programs? The answer can be found, to a large extent, in the strong advocacy by the international ‘green movement’ in favor of VRE and its strong opposition to nuclear energy. This is, among others, illustrated by the fact that the environmental organizations have exerted (and still exert) much influence within the United Nations' climate organization (UN-FCCC), having (among others) caused it to "ban" nuclear energy during the COP-6 conference (Bonn, 2001) by excluding nuclear energy from the so-called Clean Development Mechanisms (CDM) on their argued grounds that nuclear energy is unsustainable, as is shown in the following excerpts from the COP-6 agreement:

Article 6, Project Activities: To recognize that Parties included in Annex I are to refrain from using emission reduction units generated from nuclear facilities to meet their commitments under Article 3.1;

Article 12, Clean Development Mechanism: To recognize that Parties included in Annex I are to refrain from using certified emission reductions generated from nuclear facilities to meet their commitments under Article 3.1.

Discussion of the merits of nuclear energy was excluded during COP-6 and subsequent UN-FCCC meetings, completely ignoring the compelling case that nuclear fission technology offers humanity an inexhaustible source for millions of years of safe, clean, reliable energy with very low CO_2 emission [13].

A petition to rescind this 'ban' [14], directed by the International Nuclear Societies Council (INSC) to the UN Secretary General, Kofi Annan, has remained unanswered. Furthermore, the green movement caused the EU Commission to require that all the EU member states meet certain minimum quantitative requirements regarding the installation of VRE sources, while initially excluding nuclear energy.

Some countries (particularly in Western Europe) have passed laws indicating their intent to phase out nuclear power. The driving force for this is, to a large extent, attributable to the misinformation that has been disseminated during many years by the 'green movement' concerning, among others, past nuclear accidents and about unrealistic expectations on the large-scale potential of VRE. Past nuclear accidents were certainly serious events, but they have been few and their consequences were mainly economic while the loss of human life was small. Countries that have decided to turn away from nuclear energy can be expected to either continue being heavily dependent on the use of fossil fuels, or, if relying heavily on VRE, will suffer irreparable damage to their national economies with as consequence a serious lowering of the standard of living. Ironically and incongruously, some of the countries that are highly critical of nuclear energy show little reluctance in accepting a substantial part of their electrical energy supply from external nuclear sources.

Among the latest objections of the 'green movement' against nuclear energy is that nuclear power plants are costly and that it takes at least ten years to build them. This may be true for the construction of a single unit of a new design, but it does not have to be the case for large series of standardized designs that have received prior certification from the regulatory authority. The cost of a nuclear power plant is determined by the number of units in the series and the time it takes to build. That nuclear power plants can be built on time and within budget [15] has been demonstrated in the U.S.A. during the 1950s,1960s and 1970s, as well as in Western Europe (France, Italy, Spain, Sweden, Switzerland) and in Central Europe (Czech Republic, Slovakia, Hungary, Slovenia) and in Asia (Japan, South Korea, Taiwan).

The sustainability of the energy supply and the preservation of natural resources for future generations of humanity are issues that should have a high priority. Why then were no objections raised by the 'green movement' against the large-scale use of natural gas in the backup gas turbines of VRE plants? Burning gas to produce electricity (with some 40% being lost via the cooling water) is a wasteful use of an irreplaceable natural resource. Using natural gas for space heating (residences, commercial spaces) can be justified in the intermediate term on the ground that about 93% of the combustion heat is being utilized and that it reduces air pollution. Long term, space heating can be done electrically (directly or through heat pumps), using electric energy produced by nuclear power plants, as already done in high-rise buildings in some large cities. It could also be done by specialized nuclear power plants feeding subterranean urban heating networks.

If the 'green movement' were truly committed to abating climate change by reducing anthropogenic GHG emissions—as an existential concern that should trump other ideological considerations (e.g., fear of, and historical objection to, nuclear energy) —then it should revise its policies and re-direct its efforts so as to advise the governments of industrially advanced countries to replace all the fossil-fired electricity generating capacity within the coming two decades with nuclear power plants. This would allow more time for the other less-industrial countries to enact appropriate measures. In doing so, the green movement would not only serve its objective of combating climate change, it would also contribute to saving large numbers of lives [16, 17], enhance the standard of living of millions, and eliminate, or substantially reduce, the negative impact on natural landscapes turned over to produce low-density VRE [18].

Conclusions:

Countries, wishing to substantially reduce anthropogenic CO_2 emissions into the atmosphere, are not likely able to do so without nuclear energy. Excluding nuclear energy implies either continued dependence on the combustion of fossil fuels, or, if relying on large-scale deployment of VRE, will result in serious deleterious economic damage. The only exception to this may be for countries with large hydropower capacity.

The construction programs of land-based and offshore wind turbines as well as of solar installations, do little (or nothing) to achieve the intended purpose of reducing anthropogenic CO_2 emissions and abating climate change if gas-fired turbines are used for backup.

Relatively small leakage rates (less than 3%) of natural gas will eliminate most (or all) of the climate-related beneficial effect of CO_2-free energy from VRE sources (based on GWP data from the IPCC for atmospheric methane).

VRE plants are likely not economically viable, nor is it likely for them to become so, with the possible exception if large hydro power capacity is available. Furthermore, the possibility for economic viability diminishes substantially with increasing percentages of VRE on the grid.

Large-scale deployment of VRE will, in most cases, result in destruction of capital and irreparable damage to the economy with high-cost electricity for the consumers.

The presence of VRE plants on the electric grid excludes the possibility of a level playing field for any other type of generator on the grid.

VRE sources have a deleterious effect on the reliability of the electric grid, increasing the probability of delivery disruptions, including long blackouts with serious economic and social consequences. Moreover, VRE plants are highly vulnerable to extreme weather conditions.

Only few (if any) locations in the world have the combined atmospheric, climatic and geographic conditions that could make VRE an effective means for reducing CO_2 emissions that also would be an economically viable option for delivering energy to the electric grid.

A conclusion, unrelated to VRE, is that replacing coal-fired stations by gas-fired stations will not result in a climate-related beneficial effect due to a reduction of CO_2 emissions if the leakage of natural gas exceeds about 4%, (this does not take into account natural gas released from coal mines).

The dream promoted by the international 'green movement'— of a world that is free of anthropogenic greenhouse gas emissions, based solely on VRE sources -- is technically not feasible and economically not viable.

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