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Why Nuclear Power is Essential for Reducing Emissions of Greenhouse Gases

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ABSTRACT

The environment, climate change and contribution of the greenhouse gas emissions to global warming became a worldwide issue. It is recognized that energy is a major contributor to the emissions and therefore focus should be given mainly in this sector to the actions reducing the emissions and thus contributing to carbon neutrality. It is often believed that the only solution is the use of variable renewable energy sources, in particular solar and wind. Societal and financial support to such sources continues and is even further strengthened in spite of their questionable benefits and contradicting the rights of each country to decide on proper energy mix.

The paper summarizes the issues associated with the intermittency of the variable renewable energy sources if connected to the electric grid. Sustainability and potential contribution of variable sources to reduction of the emissions are discussed. Such sources, if backed by gas turbines and applied to deliver base-load quantities of energy to the electric grid, often do not contribute to a reduction in the worldwide emission of greenhouse gases, have large land requirements, need enormous amount of construction materials including critical minerals, and their environmental benefits are doubtful.

The paper concludes that nuclear power has the potential to address the issue by sustainably and reliably supplying the large quantities of clean and economical energy needed to run industrial societies with minimal emission of greenhouse gases. If the countries are truly concerned about the long-term threat of global warming, they should initiate a large-scale nuclear energy construction programme.

Keywords: *GHG emissions, environment, sustainability, renewables, nuclear power plants*

1 INTRODUCTION

Variable renewable energy (VRE), such as from wind, sun and falling water, have served humanity well during millennia for tasks that are not time-constrained, such as pumping water, sawing wood, weaving cloth, drying / preserving food, and providing transportation by means of sailing ships. The early technology associated with this VRE was rather simple. The energy required to build the necessary installations was paid back in a relatively short time and the emission of anthropogenic greenhouse gas (AGHG) was non-existent or negligible.

Modern forms of small-scale VRE (mainly wind turbines and solar panels) that do not have access to a large electrical grid, continue to be useful in many applications for generation of electrical energy. However, their generation capacity is limited by the need of energy storage such as by means of electric accumulators (batteries) or pumped hydro. For these applications the energy balance is usually also positive and the AGHG emissions are of no concern because of the limited capacity.

The situation becomes very complicated if the VRE installations are connected to the electric grid to deliver base-load quantities of electrical energy. They are then called upon to perform tasks that are subject to stringent time constrains. This requires the assistance of backup generating capacity in order to be able to meet at every moment the demand of the electric grid. This paper addresses the worldwide AGHG emissions, and the global energy balance associated with grid-connected VRE installations in comparison with implementation of nuclear power.

2 VRE CHARACTERISTICS

Grid-connected VRE installations have a number of inherent characteristics that have a strong effect on their worldwide AGHG emissions and global energy balance, namely:

1. VRE varies randomly between 0% and 100% of the installed capacity because the wind does not always blow and the sun does not always shine.
2. VRE installations produce, averaged over a time period of one year, only a fraction of their installed capacity, which is referred to as their ‘availability’ or ‘capacity factor’. The approximate values of availability are roughly 15%, 20% and 40%, respectively, for solar panels, land-based wind turbines and sea-based wind turbines (depending on locations).
3. VRE installations need to be backed up by other energy sources that have adequate capacity and flexibility to be able to meet at all times the momentary demand of the electric grid.
4. VRE, if backed up by gas turbines, will need large quantities of natural gas with associated leakage of methane (a potent greenhouse gas) into the atmosphere.
5. VRE production differs widely from year to year and season to season (by a factor two or more), requiring a large margin in backup capacity.
6. VRE require large areas to be placed.
7. VRE plants need large amounts of construction materials (such as concrete and steel), including critical minerals, requiring extensive mining, milling and processing operations.
8. VRE, connected to the electric grid, requires major adaptations to the grid at high costs.
9. VRE is not ‘dispatchable’, i.e., it cannot be called upon as needed.
10. VRE requires priority access to the electric grid for delivery (i.e., VRE plants are allowed to deliver when/what they produce), thus placing other generators on the grid at a great disadvantage because they have to accommodate the rapid variations in VRE output.

3 COMPONENTS OF THE VRE ENERGY BALANCE

The main components of the annual energy balance of VRE installations are as follows:

a) The energy consumed in building the wind / solar installations, including the energy from fossil fuel required for producing needed materials and critical minerals. This energy is a recurring item, because the VRE lifetime is limited to about 15 or 20 years (particularly if sea-based, being exposed to a very corrosive environment). In order to obtain the contribution to the annual energy component, this energy item has to be spread out (divided over) the lifetime.

b) The energy consumed for regular annual maintenance of the wind / solar installations. Because of the large number of installations and the fact that these installations are spread out over large areas, this involves much fossil energy, particularly for sea-based plants.

c) The energy consumed in adapting the electric grid to grid - connected VRE. This is a very large energy item of high cost requiring much fossil fuel. It has to be divided over 20 years.

d) The energy consumed in annual maintenance of the large VRE-related extension of the grid.

e) The energy to produce the turbines. This energy item has to be divided over about 20 years.

f) The energy consumed in the annual maintenance of the gas turbines.

g) The energy consumed by recycling the large quantity of materials that is involved for VRE (if technically feasible and economically viable).

h) The energy consumed in building and maintaining facilities for the storage of electrical energy (if needed). This energy item has to be divided over about 20 years

i) The energy consumed in backing up the wind / solar installations by gas turbines, i.e., the energy derived from the combustion of natural gas.

j) The energy generated by the combination of wind / solar installations and backup gas turbines that is delivered to the electric grid.

4 THE ROLE OF CRITICAL MINERALS

VRE is a ‘low-density’ energy source, needing much space and requiring many thousands of wind turbines and solar panels. VRE plants contain large amounts of critical minerals (including rare earths) [1] that are produced by extensive mining, milling and processing operations. Furthermore, VRE plants have a relatively short lifetime (about 15 to 20 years), thus requiring frequent replacement and often repair. Therefore, the AGHG emission due to the operation of heavy machinery (using fossil fuels) in mining and processing of critical minerals will be very substantial and will be recurring continually. 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.

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

Table 1: Required Amounts of Critical Minerals for Various Energy Technologies

Energy Technology Type	**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%)
Gas combustion	1,000	1,000*(100/90) = 1,100 (availability of 90%)

5 SOME CHARACTERISTICS OF GAS TURBINES

Most gas turbines being used for VRE backup, are of the combined-cycle gas turbines (CCGT). This is because of their high thermal efficiency (about 60%). However, CCGTs are lacking in 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 but have a much lower thermal efficiency (about 40%) and are therefore usually not used for backup.

The lack of flexibility in CCGTs causes a substantial loss in thermal efficiency. Furthermore, in order for CCGTs to remain readily available (i. e. in ‘stand-by’ condition), their power level cannot be reduced below a certain minimum level. This means that the CCGTs have often to be kept running at their minimum ‘stand-by’ power level, even if no CCGT output is needed. The consequence is an overall thermal loss that may exceed 20%.

6 ENERGY STORAGE

With the aim of reducing the VRE dependence on natural gas, substantial investments are being made in installations for the storage of excess VRE. There exist numerous types of energy storage systems and their selection depends mainly on the magnitude and speed of the tasks to be performed. Among the most commonly used ones in connection with large-scale VRE there are: pumped hydro (gravitational) energy storage, electric accumulators (batteries) energy storage, compressed air energy storage, hydrogen energy storage. For small-scale applications use is also sometimes made of heat energy storage and kinetic energy storage (e.g., rotating flywheels).

Energy storage systems have to comply with a number of criteria in order to perform their intended tasks. Among the most important ones are energy density, discharge quantity, discharge speed, cost, safety and roundtrip efficiency (i.e., electric energy → stored energy → electric energy).

Pumped hydro storage is widely used. It meets most criteria. However, its application is limited to locations with a nearby large water reservoir (lake) at a minimum elevation above the surrounding area. The roundtrip efficiency is about 70%.

Electrical accumulators (batteries) function well for small scale VRE applications that are not connected to a large electric grid. However, for large scale grid - connected VRE, electrical accumulators are not an economically viable option. The roundtrip efficiency is about 70%. Furthermore, large battery packs are not without a safety concern due to the fact that all chemical components, necessary for a fast energy release caused by an internal short-circuit, are already ‘inside the box’. This safety concern is less for electricity accumulators of the flow-through type. However, the discharge speed of this type of accumulators, being determined by the size of the interaction area, limits their application.

Compressed air energy storage is potentially a good system for large scale VRE. However, it depends on the presence of large enclosed volumes such as underground caves. The roundtrip efficiency is less than 70%,

Hydrogen is a valuable energy carrier that is also used for energy storage. Major investments are being made installing hydrogen-production plants that are to be run on VRE excess output. The hydrogen production efficacy of these plants will be low because of the rapidly varying VRE output and very high investment of electrolyser. The roundtrip efficiency (electricity→hydrogen→electricity) will be low (20% to 40%). The quantity of hydrogen produced will be insufficient to replace the natural gas. Furthermore, the properties of hydrogen are sufficiently different from those of natural gas that mixed use may not be feasible. The fact that hydrogen leaks and that pipelines for natural gas are not suitable for hydrogen, will involve major costs. Furthermore, hydrogen has a tendency to form metal-hydrides, resulting in embrittlement which could endanger pipe integrity. In view of this, it may be expected that hydrogen production plants, if run on excess VRE output, will not be economically viable and will have significant complications.

Hydrogen production via high-temperature steam electrolysis (HTSE) using stable and reliable nuclear energy, has a much higher efficacy than by the use of continuously varying excess VRE. As an energy carrier used in industry, hydrogen will be able to replace most fossil fuels (e.g., in steel production), thus providing a very large potential for reducing AGHG emissions in many areas other than the generation of electrical energy.

7 ECONOMICAL COMPETITIVENESS OF VRE

Since VRE are low-operating-cost power sources, (similarly as NPPs), at sunny days all solar plants would like to deliver to the grid and prices of electricity should be low (if not subsidized). At the time with low solar output other sources will be required to operate, but due to low-capacity factor would not operate economically, unless price of electricity will become very high. If VRE are not subsidized, price collapse at the time of high solar output will limit the use of VRE due to revenue collapse.

All electricity generating technologies have system costs; nuclear, for instance, requires strong network connections and access to reliable cooling sources. However, the costs of usual electricity generating technologies are an order of magnitude lower than those imposed by the variability of renewable energies. System costs which need to be added to the plant generation costs can be substantial and depend on the level of VRE penetration. VRE revenues from electricity markets decline significantly and non-linearly as their penetration level increases; zero-level electricity prices start when VREs reach a penetration level of 30% [2]. The higher frequency of hours with zero prices needs to be compensated by an increase of the number of hours with high electricity prices. High volatility of prices significantly increases the electricity market risk for all generation technologies.

It can be concluded that VRE are not competitive and are dependent on subsidies or on favorable legislation. There is big difference between the production cost of a kWh generated and consumed locally and the cost of a kWh delivered to the electrical grid. In addition, VRE deleteriously affect grid reliability, with serious economic and social consequences of blackouts occurred in large urban areas.

8 SUMMARY EVALUATION OF VRE

Land-based VRE installations have an availability that often is less than 20%. This means that the annual amount of energy, produced by these installations, is only 20% of what would be produced if the wind would blow continuously at optimal speed and if the sun would shine uninterruptedly at optimal brightness. For grid - connected VRE installations, this VRE energy has to be supplemented by backup capacity which optimally has to be equal to 100% of the installed VRE capacity and then produces 80% of the energy delivered to the grid by the VRE and its backup. Some countries have a grid - connected VRE capacity that is higher than what the grid calls for. The excess VRE output is then dumped on the shared communal electric grid with adverse effects on grid reliability. Adjacent countries are then forced to install equipment at high cost to protect the reliability of their own local grid by blocking access to it.

As mentioned earlier, CCGTs are limited in flexibility necessary for backing up VRE. The consequence of this limitation is that the combination of VRE plants together with CCGT backup often has a higher AGHG emission than solely the CCGTs without VRE. 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 when not needed. Without VRE, the CCGTs will have to deal only with the slow and foreseeable diurnal changes in the demand of the electric grid.

This phenomenon is most likely to occur for land - based VRE installations with low availability, as is the case in many regions of Europe. Notwithstanding strong opposition from the affected local residents, many governments imposed large-scale installation of land-based wind turbines that cause audial / visual disturbances to residents, kill protected birds / bats and destroy beautiful landscapes, often with no benefit for the climate.

The value of the annual amount of energy represented by items a) through h) in Section 3 of this paper (mostly from fossil fuel), is not readily available. However, it should not come as a surprise if it is found to approach or exceed the total amount of energy delivered annually to the grid by the VRE. It is important to note that a substantial part of the necessary fossil fuel will have to be used outside the territories for which reduction in AGHG is claimed (e.g., in Africa, Asia, Australia and South America for mining, milling and processing of critical minerals).

Because the emission of CO_2 is directly related to the combustion of fossil fuel, it follows that VRE installations are not an effective method for reducing AGHG emissions. This is true, even if not accounting for the leakage of methane (CH_4) into the atmosphere that is associated with the natural gas used in the CCGTs. Methane is a greenhouse gas that is much more potent than CO_2. Leakage of only a small percentage of the flow of natural gas will completely eliminate any climate-related benefit that comes from VRE.

Some environmental groups are promoting the ‘dream’ of a world with energy provided solely by VRE plants without backup. This is unrealistic for many reasons, including the fact that, even with backup, the global VRE energy balance may not be positive. The excess energy (if any) will be insufficient to build the next generation of VRE plants.

9 NUCLEAR ENERGY

Nuclear fission technology is among the most effective means for reducing worldwide AGHG emissions [2, 3, 4, 5]. It is important to note that none of the energy components mentioned in Section 3, items a) through h), play a role in nuclear energy.

Furthermore, 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, if compared with, respectively, wind turbines at sea, solar panels and wind turbines on land. This fact is further underlined by considerably longer life time of nuclear power plants compared with wind turbines and solar panels. Moreover, the majority of the minerals needed for nuclear power plants do not belong to the rare species, thus requiring considerably less mining and processing.

Total identified, prognosticated and unconventional resources of uranium are sufficient for hundreds of years. Use of uranium with reprocessing provides fuel for thousands of years. Other resources are available in thorium. These facts confirm sustainability of nuclear power for a very large-civilization-spanning-time scale without depriving future generations.

Nuclear power is very safe compared to other ways for production of electricity. Radiation from nuclear power plants in normal operation is negligible compared to other sources of natural radiation. Number of fatalities due to production of electricity from any fossil fuels (including gas and biomass) is very much higher than from nuclear accidents. Number of fatalities due to production of electricity from VRE is also much higher than from nuclear accidents; they are comparable only if the linear no-threshold model of radiation effects (very questionable) is used.

Complexity of final repository of low and medium level radioactive waste is comparable with many kinds of other wastes, volume of high level waste is small and can be safely placed in deep geological repository.

10 CONCLUSIONS

Based on the analysis and discussions above the following conclusions can be made:

1. Grid-connected VRE installations, if backed up by gas turbines, are not sustainable because natural gas is a limited and often hardly accessible resource. Furthermore, they often do not reduce worldwide AGHG emissions nor are they likely to have a positive global energy balance.
2. Countries should not claim VRE-related reductions in their AGHG emissions if they do not account for emissions outside their borders caused by their in-country VRE plants.
3. Industrialized countries should reconsider the large-scale misallocation of financial, natural and human resources that are used to build grid- connected VRE installations.
4. Hydrogen is a valuable energy carrier that, if produced by nuclear energy, can play an important indirect role in reducing worldwide AGHG emissions.
5. Production of hydrogen by excess VRE is inefficient and economically not viable. It hardly can be used to replace natural gas to back up VRE.

6. The idea of a modern society, dependent solely on VRE installations, is impossible with the current world population and standard of living.

7. Nuclear power has the potential to address the issue of global warming by sustainably and reliably supplying the large quantities of safe, clean, economical and environmentally friendly energy needed to run industrial societies with minimal emission of greenhouse gases.

8. Industrialized countries that are seriously concerned about the threat of global warming should initiate large-scale programs on nuclear power plant construction, aimed at eliminating within two or three decades all use of fossil fuels for the generation of electrical energy.

9. Nuclear programs should include as a major objective the commercialization of fast-neutron fission technology (including closing the fuel cycle), thus transforming nuclear fission into an energy source at the service of humanity that is reliable and truly inexhaustible.

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