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The energy challenge of a post-fossil world: Seasonal energy storage

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Summary. — Fossil fuels are an energy source and an energy storage system. The demand for electricity and heat varies daily, weekly, and seasonally with seasonal variations often varying by a factor of two or more. The variable demand is met by fossil fuels because 1) fossil fuels are inexpensive to store in coal piles, oil tanks, and underground natural gas storage facilities and 2) the capital cost of the equipment to burn fossil fuels and convert the energy to heat or electricity is small relative to the cost of the fossil fuels. Concerns about climate change may limit the conventional use of fossil fuels. The alternative low-carbon energy production systems (nuclear, fossil fuels with carbon dioxide sequestration, wind, and solar) are capital-intensive energy sources with low operating costs. To obtain favorable economics, these technologies must operate at full capacity; but, their output does not match energy demand. We have energy alternatives to fossil fuels but no replacements for the energy storage capabilities of fossil fuels. Proposed strategies and technologies to address the grand storage challenge (including seasonal storage of electricity) are described. The options suggest a nuclear-renewables future to address seasonal energy storage needs in a low-carbon world.

PACS `89.30.Gg` – Nuclear fission power.
PACS `88.20.gc` – Fischer-Tropsch (F-T) liquids (hydrocarbons).
PACS `88.30.em` – Electrolytic hydrogen.

1. – Introduction

Les Rencontres de Physique de la Vallée d'Aoste addresses the challenges in particle physics. There are equal challenges for world energy policies that in the next several decades will likely be driven by two factors: the end of inexpensive oil and limits on the traditional uses of fossil fuels because of concerns about climate change. It is usually assumed that the primary energy challenge is to replace fossil fuels as an energy source; however, an equal or greater challenge may be to replace the storage functions of fossil fuels. This paper examines energy storage in the context of electricity and transportation.

2. – The storage challenge

Electricity demand varies daily, weekly, and seasonally. At higher latitudes, there is also a 3-day cycle associated with weather patterns. Parallel to the electricity demand, the demand for heating and cooling has similar cycles. On a different time cycle are the variable energy demands by the transport sector. Today the burning of fossil fuels is the primary technology to match energy production with fluctuating energy demand. Fossil fuels are used for variable electricity, heat, and motive production because 1) they are inexpensive to store until needed and 2) the equipment for conversion of fossil fuels to useful energy has relatively low capital costs.

The use of fossil fuels to meet variable energy demands may be limited in the future because of concerns about climate change. In the United States, the Obama administration's goal in the United States is to reduce greenhouse gas emissions by 80% by 2050. Such goals imply eliminating fossil emissions from almost all major sources.

Greenhouse gas emissions can be reduced from fossil plants by sequestering the carbon dioxide underground [1]; however, such fossil power plants are likely to be uneconomic for variable production of electricity or heat because of their high capital costs and the technical difficulties in operating such plants with variable output. It is not practical to collect and sequester carbon dioxide from small users of fossil fuels—such as for heating homes and commercial buildings. To avoid these greenhouse gas releases, there will likely be increased use of electricity for building heating and cooling. This implies larger seasonal swings in electricity demand. In the transport sector [2], the likely introduction of plug-in hybrid vehicles will partly replace gasoline and diesel fuel with electricity; however, the demand for transport is higher in the summer implying growing seasonal variations in electricity demand.

The primary low-carbon electricity systems for the future are nuclear, hydro, wind, geothermal, solar, and fossil fuels with carbon-dioxide sequestration. All of these technologies have high capital costs (when delivered capacity is factored in) and low operating costs; thus, it is essential to operate them at their full capacities to minimize increases in electricity costs.

If capital-intensive electrical generating technologies are not operated at full capacity, there will be large increases in the cost of electricity. This can be seen by example. A recent study [3] evaluated the cost of electricity from new nuclear, coal, and natural gas plants in the United States. Using the same financial rules(^{1}), the respective levelized electricity costs were 6.6, 6.2, and 6.5 ¢/kWh. The capital cost component of the electricity costs were respectively 72, 45, and 15%.

Today, natural gas is used for variable electricity production. If a natural gas plant operates half the time *versus* all the time to match production with demand, it has little impact on the cost of electricity because only 15% of the cost is associated with the initial plant construction. The rest of the cost is associated with fuel and operations. In contrast, for nuclear power plants (and capital-intensive renewable power plants), most of the cost of electricity is associated with paying for the plant. If the plant operates half the time, the costs of electricity will be almost doubled because the capital cost remains

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(^{1}) Without federal loan guarantees, it is assumed that the first few new nuclear plants in the U.S. will pay a higher cost of capital than for other types of generating plants. This financial risk premium would increase the electricity costs to 8.4 ¢/kWh. Such a risk premium would not exist for latter plants.

fixed while the production is cut in half. Operating capital-intensive electric generating technologies at anything but full capacity results in high electricity costs.

Concerns about climate change will likely impose restrictions on carbon dioxide releases from burning fossil fuels. If a \$25/tCO$_2$ tax is imposed to avoid carbon dioxide releases to the atmosphere, the respective electricity costs from new coal and natural plants increase 8.3 and 7.4 ¢/kWh. Restrictions on greenhouse gas emissions have significant impacts on the costs of electricity from fossil fuels.

No single low-carbon electricity source or combination of electricity sources comes close to matching the variable electricity demand. The mismatch between production and demand requires rethinking of our electrical systems if conventional fossil fuel use is limited. There are four options to address the mismatch between electricity production and demand in a low-carbon world.

- Operate capital-intensive energy production systems at part load at times of low power demand. This is an expensive option—particularly for renewables such as wind where there is often a seasonal mismatch between peak production and demand.
- Chose energy sources to match energy demand. If storage and part-load operation of power generation equipment is expensive, costs can be reduced by choosing the combination of energy production technologies whose outputs most closely match energy demand to minimize partial-load operation of capital-intensive power plants and minimize energy storage needs.
- Develop energy storage technologies. Many technologies exist to store energy for a few days (pumped hydro, batteries, thermal storage systems) but there is only one non-fossil seasonal energy storage technology—large-scale hydroelectricity. For most of the world there is insufficient hydro to meet storage needs.
- Develop new energy markets that can consume excess energy when available from capital-intensive energy production sources.

A candidate strategy to address the seasonal energy storage challenge is described herein (fig. 1) that uses new seasonal storage technologies and new markets for off-peak power. Such a strategy combines nuclear and renewable energy sources to maximize utilization of high-capital-cost energy production technologies.

3. – Seasonal storage of electricity

In a low-carbon world of high-capital-cost, low-operating-cost nuclear, wind, and solar plants, electrical generating facilities should operate at their maximum output to minimize costs. This requires gigawatt-year electricity storage capacities if excess electricity production in the spring and fall are to meet peak electricity demands in the winter and summer. One set of options uses hydrogen as the storage media [4, 5] and is potentially deployable within a decade. An example of such a system is the Hydrogen Intermediate and Peak Electrical System (HIPES) for variable electricity demand on a daily, weekly, and seasonal basis. It consists of three major components.

Hydrogen production. Hydrogen is produced from water with the by-product production of oxygen. The commercial low-carbon hydrogen production option today is electrolysis where the energy input is in the form of electricity. The midterm option is

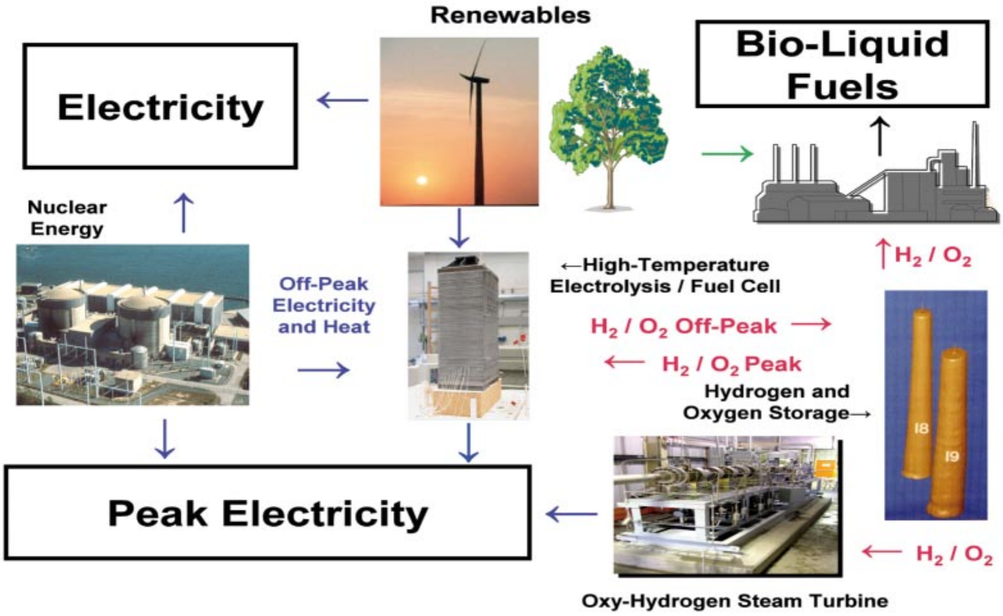

Fig. 1. – Example system to replace the fossil fuel storage functions.

high-temperature electrolysis (HTE) where heat, electricity, and water produce hydrogen and oxygen. HTE has potentially lower costs than traditional electrolysis because lower-cost heat partly substitutes for more expensive electricity. The HTE energy sources would be nuclear reactors that supply heat and electricity and renewable systems that could provide electricity. The hydrogen production efficiency with a light-water reactor using HTE is projected to be close to the production efficiency for electricity [5, 6]. Hydrogen production would be at times of low electrical demand to maximize utilization of capital-intensive electric generating technologies.

Hydrogen and oxygen storage. Underground storage facilities would be used for the low-cost storage of hydrogen and oxygen on a daily, weekly, or seasonal basis. Unlike electricity, hydrogen can be stored inexpensively for days, weeks, or months in large underground facilities using the same technology developed to store natural gas. In the United States, approximately 400 underground storage facilities store at high pressure a third of a year's production of natural gas in the fall before the winter heating season.

A limited number of such hydrogen storage facilities now exist in Europe and the United States to support the chemical and refining industries. *Hydrogen is today the only non-fossil energy storage media for which the commercial technology exists to store energy on a scale sufficiently large to cover seasonal variations in electricity demand.* There have been studies on bulk oxygen storage; but, this technology has not been commercialized.

Hydrogen-to-electricity conversion. There are multiple technologies to convert hydrogen and oxygen to electricity. The leading midterm technologies are fuel cells and oxy-hydrogen steam turbines because of their potentially high efficiencies and low capital costs compared to traditional natural-gas-fired combined-cycle plants used today for peak power production. The two technologies have complimentary capabilities.

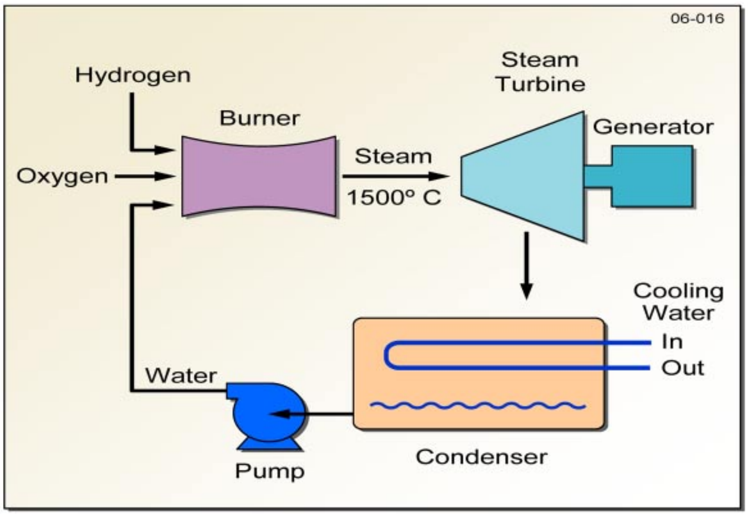

Fig. 2. – Oxy-hydrogen steam cycle.

Solid-oxide high-temperature fuel cells are being developed for electricity production. For peak power applications within HIPES, this technology has a unique advantage because a solid-oxide high-temperature fuel cell operated in reverse is a HTE system producing hydrogen. By using the same piece of equipment for both electricity and hydrogen production, the system capital costs are minimized. The fuel cell/HTE combination would allow the utility operator to vary electricity output from the nuclear station to the electrical grid from zero (all energy to HTE for hydrogen and oxygen production) to $\sim$ 170% of base-load electrical production (electricity to grid from the reactor and fuel cells). Wider variations in electricity output are possible if renewables are used to provide electricity to the HTE system with the nuclear reactor used to provide primarily heat at times of low electricity demand.

Siemens is developing a fuel cell/turbine combination that uses hydrogen and air with a projected efficiency of about 70%. This variant would avoid the need for oxygen storage. Alternatively, if oxygen is stored, the fuel cell size is reduced relative to a fuel cell operating on air because the oxygen electrode determines fuel-cell performance. A fuel cell operated on oxygen will have two to four times the output of a fuel cell operated on air.

The other peak-power technology is the oxy-hydrogen steam cycle (fig. 2). Hydrogen, oxygen, and water are fed directly to a burner to produce high-pressure, high-temperature steam. The resultant steam is fed directly to an aero-derived high temperature turbine that drives an electric generator. With actively cooled blades, it is expected that peak steam temperatures at the inlet of the first turbines can approach 1500 °C. The projected heat-to-electricity efficiency for advanced turbines approaches $\sim$ 70%, starting with compressed oxygen and hydrogen from the storage facilities.

The technology is based on ongoing development of an advanced natural-gas electric plant that uses oxygen rather than air [7] by Clean Energy Systems, Inc. Combustors with outputs of $\sim$ 20 MW(t) are being tested. With a feed of natural gas and oxygen, a mixture of steam and carbon dioxide is created. After this mixture passes through the turbine to the condenser, the steam is condensed and the carbon dioxide is available for 1) injection into oil fields to increase the recovery of oil and/or 2) sequestration.

This peak power technology has one unique characteristic. Based on what we know today, the capital costs [4] are significantly less than traditional natural-gas-fired gas turbines or any other available peak power technology. The system does not require compression of air as in traditional gas turbines or have the boilers to produce steam. Consequently, there are large incentives to develop such a peak electricity technology to provide the backup for renewables where power production can drop quickly. The technical constraint is that the system requires large-scale hydrogen and oxygen storage to enable the direct production of steam.

4. – Transportation

Oil provides about 35% of the world's energy demand and is the fuel of choice for the transport sector because it's an easy to store energy source. In a low-carbon world, oil consumption must be dramatically reduced. Existing technologies such as electrification of trains and near-term technologies such as plug-in hybrid vehicles may reduce oil demand in half. However, the transport sector needs a transportable fuel.

Liquid hydrocarbon fuels excel as transport fuels because they are an excellent energy storage system [2]. The primary options for low-carbon liquid fuels are fuels from biomass. Carbon dioxide is removed from the air and converted into biomass. The biomass is converted into liquid fuels and the fuels are burnt in vehicles with return of the carbon dioxide to the atmosphere. This is an attractive concept; however, *it is limited by the availability of world biomass production*. The contribution of biomass to liquid fuels production depends upon how efficiently we convert biomass to liquid fuels.

We have the technology today to convert any carbon source to liquid fuels. However, the less the carbon source looks like diesel fuel or gasoline, the more energy is required for the conversion process. For example [8], the energy input in refining to convert oil into diesel fuel is 15 to 20% of the energy value of the crude oil. If the starting material is coal, the energy consumption inside the coal liquefaction plant exceeds the energy value of the diesel fuel that is produced.

Available data indicate that U.S. biomass resources are about typical of the world as a whole; thus, U.S. biomass data will be used herein in understanding the liquid fuels potential of different biomass processing options in terms of liquid-fuels production. The United States [9] could produce about 1.3 billion dry tons of biomass feedstock per year for conversion to liquid fuels without major cost or availability impacts on the production of food or fiber. Except for the grains, most of the biomass resources are cellulosic biomass that can not be used as food for humans.

The energy value [2,10] of the 1.3 billion tons of dry biomass per year that is available in the United States depends upon the form in which it is used.

- *Burn biomass.* The energy content of the biomass, if burnt, would be equal to burning 9.8 million barrels of diesel fuel per day.
- *Fuel ethanol.* If the biomass were converted to fuel ethanol, the energy value of the ethanol would be equal to about 4.7 million barrels of diesel fuel per day. This scenario assumes that some of the biomass is converted into ethanol and that the remainder of the biomass provides the energy for the biomass-to-ethanol conversion processes. Like the conversion of heavy oils and coal to liquid fuels, biomass requires significant energy inputs for production of high-quality liquid fuels.

- *Diesel fuel.* If all of the carbon in the biomass were converted to diesel fuel, 12.4 million barrels of diesel fuel could be produced per day. This assumes that non-biomass energy sources provide the needed energy to operate the biomass-to-fuel plants and to produce the hydrogen needed for the conversion process.

For the United States, liquid fuels from biomass could potentially meet the nation's need for liquid transport fuels, but only if the biomass is used as a feedstock and not as the energy source to operate the biomass-to-liquid-fuels conversion plants. The same principle is applicable worldwide. Today nuclear energy is the only low-carbon energy source that can provide the heat and hydrogen under the conditions that are required by a bio-refinery (steady state operation).

Most of the energy input is in the form of hydrogen. In this context, the integration of the electric sector with the fuels production sector could provide the source of hydrogen. Excess electricity at times of low energy demand could be converted to hydrogen, that hydrogen can be stored, and the hydrogen can be used for liquid fuels production. In effect, excess electricity is converted into "storable" liquid fuels while fully utilizing all electricity generation capabilities.

5. – Conclusions

Fossil fuels serve two functions: an energy source and an energy storage media. While much attention has been given to alternative energy sources, little attention has been given to replacing the energy storage functions of fossil fuels. While there are multiple technologies for short-term storage of energy, there are very few options today to address seasonal energy storage requirements. From the limited work that has been done, several preliminary conclusions can be reached.

There are significant technical and economic incentives to create nuclear-renewable hybrid energy systems. Biomass liquid fuels production requires outside heat and hydrogen sources if sufficient biomass liquid fuels are to be produced to replace conventional oil in our transport system. In the electricity sector, the large scale use of renewables requires large-scale seasonal energy storage systems with gigawatt-year capacities. Hydrogen is a leading candidate for this energy storage role. The most efficient methods to make hydrogen from water require both electricity and heat. The storage, handling, and production technologies are intrinsically large-scale technologies. These characteristics imply a natural coupling between nuclear energy, hydrogen production [11], and seasonal energy storage systems.

The most important role for renewables will likely be biofuels production. Peak electricity systems that include seasonal storage would enable renewables to become large-scale electricity sources—beyond the current limits of 10 to 15% of electricity production. Our ability to develop energy storage systems, particularly seasonal energy storage, may determine the total energy system architecture and the difficulty of developing an economic low-carbon energy world.

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