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**Weaning Humanity Off of Fossil Fuels Using the Power of Economics**

Technology has become increasingly sophisticated over the last half century, allowing researchers to accurately measure atmospheric radiation fluxes, ocean temperatures, greenhouse gas concentrations, and other factors that have an important influence on the global climate. Modern climate models can very accurately replicate these measurements, which allows scientists to model past climates using proxy data from ice cores and tree rings. Both the current measurements and models of past climates indicate that human activities are causing an extremely rapid global warming effect. While global warming is typically a natural process, it usually happens at a much slower rate. The augmented warming appears to have begun near the same time as the industrial revolution and accelerated even more ever since due to the increasingly large volume of greenhouse gasses that are being dumped into the atmosphere by cars, power plants, and mining operations. Coal and natural gas provide the vast majority of electrical power to most countries, including the United States. Enormous quantities of gasoline and diesel fuel are burned in vehicles every year. The reason that our technology developed around fossil fuels is that they were cheap and relatively easy to access with nineteenth century technology. The majority of humans will continue to use these cheap sources of fuel as long as they are the most inexpensive and convenient option. With the push to use sustainable power generation and electric vehicles, renewable technologies are becoming more and more economically viable. Along with the ever decreasing supply and increasing cost of fossil fuels, the maturation of sustainable technology will eventually enable humans to live virtually emission-free.

The equalization of the cost of fossil fuels and renewable energy sources will take some time. Technology exists now that can make the transition less damaging to the environment. Fully electric vehicles can drastically reduce the quantity of fossil fuels burned through power generation efficiency improvement alone. Tesla Motors claims that their Model S vehicle achieves an 88 percent battery electrical power to mechanical drive power conversion efficiency (Tesla Motors, 2014). However, since the electricity used to charge the batteries was likely produced at a coal or natural gas power plant, those efficiencies must also be taken into account. A typical power plant running a steam turbine and a gas turbine in a combined cycle can achieve efficiencies on the order of 60 percent Combined with the Model S electrical powertrain, the vehicle achieves an overall efficiency of approximately 53 percent. Combustion engines used in automotive applications are relatively inefficient at converting the chemical energy stored in gasoline into useful mechanical energy, typically having 25-30 percent efficiency. In 2012, the United States burned approximately 133 billion gallons of gasoline (How much gasoline does the United States consume?, 2013). Assuming the gasoline were burned in a power plant while maintaining the efficiencies described above, approximately 23 percent less fuel would have to be burned to produce the same amount of energy. The resulting reduction in gasoline burning would produce an annual savings of $108.6 billion assuming a 2012 average per-gallon fuel price of $3.55 (Gasoline and Diesel Fuel Update, 2014). Once the economic advantage to electric car usage becomes more obvious, car companies will develop quality vehicles that people will actually want to buy and the gasoline car will quickly become an antique.

While there are obvious efficiency benefits of electric vehicles, the power plants used to generate the electricity still produce environmentally damaging emissions. It is relatively easy to install carbon capturing and filtering technology at a large scale facility rather than in a car which must be compact. Most carbon capture and sequestration CSS technologies involve either injecting supercritical $CO_2$ into sturdy geologic formations for long term storage or exothermically transmuting the gas into stable carbonate minerals that can be easily stored. While it is possible to reduce the atmospheric uptake of $CO_2$ by 80-90 percent, the resulting penalty is an increase in power plant fuel consumption on the order of 25-40 percent (Metz, Davidson, Coninck, Loos, & Meyer, 2005). Retrofitting existing power plants with CSS systems may become economically viable once federal restrictions concerning carbon dioxide emissions and the price of the additional fuel reach an equilibrium point, but investing in power sources that are inherently free of hydrocarbons is a much better idea.

Although the nuclear power industry has had several high profile incidents, nuclear power can be a very clean and efficient source of energy. Nuclear power generation operates on the same 60 percent efficient turbines that are used in fossil fuel fired plants. Instead of burning fossil fuels, the heat of fission is harnessed to generate steam. According to the Intergovernmental Panel on Climate Change (IPCC), fission power produces 60 times fewer greenhouse gas emissions over its lifecycle compared to coal power and 30 times less than natural gas (Moomaw, Burgherr, Lenzen, Nyboer, & Verbruggen, 2011). Nuclear power could be an effective source of clean energy if not for the public's fear of both the long-term radioactivity of the waste and the threat of a containment breach such as in Chernobyl or Fukushima. Generation IV fission reactor concepts address both of these issues. Inherently safe designs include features that automatically shunt the toxic material in a compromised reactor into a pre-built containment pit in the event of coolant system failure or power loss. The amount of nuclear waste produced in Gen IV reactors will be less radioactive and decay more quickly than existing reactors (Hansen, 2009). In addition, the waste will be reprocessed and fed back into the reactors as new fuel instead of the current wasteful practice of throwing it away. The small amount of dangerous waste that remains will be sealed inside of stable geologic formations to avoid potential groundwater contamination. Fission will always produce some quantity of highly radioactive nuclear waste, and unfortunately will likely never redeem itself in the eyes of the public. As an alternative to fission power, development of fusion technology provides a safer, more sustainable, and more potent possibility to harness the atom.

Nuclear fusion works on the opposite principle of fission, fusing light atomic nuclei together instead of splitting large nuclei apart. Typical fuels in a fusion reaction are various isotopes of hydrogen and helium, with Deuterium-Tritium being the most common. To achieve fusion, the repulsive electrostatic force between protons must be overcome. Atoms are heated to strip off their electrons, forming a plasma that is then heated further to over 100 million Kelvin increase the kinetic energy of the fuel. The incredibly hot plasma must be magnetically confined as it will easily melt anything it comes into contact with. If temperatures remain hot enough and the confinement is maintained, self-sustained fusion can occur. Typical fusion reactions produce substantially more energy per mass of fuel used than fission reactions. A fusion power plant occupies a very small footprint compared to technologies such as wind and solar power. Fusion also completely eliminates the problems of meltdown accidents and dangerously radioactive nuclear waste. Fusion is inherently safe due to the active control requirements of plasma confinement. If containment is breached or the facility loses power, the reaction will stop immediately as the plasma quickly loses temperature. Fusion waste is also very easy to contain and store, as the longest-lived by product has a half-life of only 12.32 years as opposed to high level fission waste products which have half-lives of up to 15.7 million years (Unterweger, Hoppes, Schima, & Coursey, 2011).

Deuterium, one of the most promising fusion fuels, is easily accessible in seawater as 0.0156% of water-bound hydrogen atoms (IAEA Isotope Hydrology Laboratory, 2007). Since the oceans hold approximately 13 billion cubic kilometers of water, many billions of tons of deuterium exist in a readily accessible form. The energy density of fusion is very high; the deuterium contained within a gallon of seawater can produce as much energy as 300 gallons of gasoline (Hyper Physics, 2013). There are many challenges that must be overcome to produce fusion power at a power plant scale. Plasma confinement remains the most perplexing problem to solve, as physics must be carefully controlled on incredibly small time scales to dampen unpredictable instabilities in the plasma. Several methods have been tried, such as inertial confinement using high power lasers and magnetic confinement using a toroid-shaped magnetic field to contain the strongly electrically charged plasma. Both methods have worked, but neither has produced a fusion reaction that created more energy than it consumed for any reasonable length of time. It is thought that the problem can be solved by increasing the scale of the reactor, which will be put to the test when the International Thermonuclear Experimental Reactor (ITER) project is completed in 2020. Another problem plaguing fusion reactors comes from building material limitations. The incredibly high neutron flux generated by fusion degrades the materials used to confine the plasma very quickly, requiring a complete refit every few years. Obviously new shielding materials must be invented to prevent extremely costly shutdown of a large power plant. While fusion power will not be ready for another decade at the earliest, it presents a promising option for sustainable long-term power generation. In the meantime, proven renewable technologies can be used to wean humanity off of fossil fuels more quickly.

Wind power offers an attractive source of infinitely renewable energy that is already used in many places around the world. Both offshore and onshore wind farms are used all over the world as a relatively inexpensive source of electrical power generation. Some existing wind farms based mostly in the United States generate over 1 GW of power, and wind power accounts for 2.5% of global energy production (World Wind Energy Association, 2011). The market share of wind power is steadily increasing and is expected to reach 8% by 2018 (BTM Consult, 2009). The theoretical maximum efficiency of a wind turbine is 59.3% according to the Betz Law (Randall, 1966). In practical wind turbines the efficiency is typically about 75% of this upper limit, making wind power extraction only about 44% efficient. However, an efficiency comparison with fossil fuel power generation is not a very good one since the wind is free and has no harmful effect on the environment. Wind power has some drawbacks. The wind is not constant, so power generation is not constant either. Humanity cannot rely on wind power alone to generate the base load power required for normal operation of the grid. There are also relatively few places around the world that are ideal for using wind turbines, primarily because the location needs to have strong, steady wind for the majority of the year. Nature conservationists have expressed concern that wind farms cause high avian mortality rates due to turbine blade bird strikes, but research concludes that wind turbines kill fewer birds than the indirect effects of most conventional power generation facilities (Sovacool, 2013). While wind power is an excellent supplement to other renewable sources of energy, it cannot sustain humanity on its own.

Solar power presents an interesting source of renewable energy that is driven by the sun itself. Solar energy is typically harnessed either with photovoltaic panels that convert sunlight directly into electricity or by using solar concentrators to generate heat that runs a turbine. Photovoltaics continue to get increasingly better as the technology matures and are already cheaper per watt than nuclear power and approximately on level terms with coal and natural gas fired plants. Photovoltaics are easy to install onto existing structures and require little maintenance over their decades-long lifespan. Photovoltaic panels are not particularly efficient, with most commercially available products achieving 14-22% solar energy conversion efficiency (Schultz, Mette, Preu, & Glunz, 2007). As with wind power, the efficiency does not compare to that of fossil fuel or nuclear power generation as sunlight is free and effectively infinite. The primary reason to increase the efficiency of solar cells is to generate equivalent power on a smaller parcel of land. The largest photovoltaic plants generate roughly 250MW over 2,400 acres, while a typical 500MW natural gas plant occupies only 70 acres. In addition to taking up large swaths of land, photovoltaics are only effective in very sunny regions, and even then only during the day. The large footprint of photovoltaics combined with their nighttime ineffectiveness make them an unattractive option to provide the primary power load. However, they can be used to supplement conventional power generation in most regions where space is not an issue.

It appears that no one technology can independently address the need to switch away from fossil fuels as the primary energy production fuel. Solar and wind power are essentially infinite and free, but produce energy intermittently and require lots of space. Nuclear waste generated by fission power creates a public image that is unlikely to be overcome while fusion power always seems to be 50 years away from full usability. It would seem that humanity’s best option would be to continue to develop each of these technologies in parallel to share the load of our ever-increasing energy appetite. In addition, other methods of power generation can be used if geography permits, such as wave energy, hydro power, geothermal power, and other even more exotic systems. The only way to truly transition away from using primarily fossil fuels is to make at least one of these technologies cheaper than the environmentally polluting coal and natural gas plants. Each of these renewable energy technologies continue to become less expensive and more widely used, while fossil fuel costs can only go up in the long term as the finite petroleum reserves continue to slowly decrease and extraction becomes more expensive. Combined with removing the majority of gasoline and diesel powered vehicles from the road using economics, humanity can virtually halt their increasingly damaging emissions into the atmosphere by the end of the century.

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