**JEI Working Paper 5 – The Grid Revolution**

**Jordan Sabin**

**Yale University**

***Executive Summary***

The global climate is quickly changing as the atmosphere reacts to the trillions of tons of carbon dioxide released in the past two centuries. This warming is wreaking havoc on ecosystems around the globe, and is expected to accelerate in coming decades. In recent years, international organizations have called for dramatic investments in clean technologies in order to keep the planet cool. This paper outlines how to apply such investments to the American utility grid.

The United States power grid is perhaps the most antiquated piece of infrastructure in the country, relying on technologies first developed following World War II. In the 6 decades since the grid took shape, industry has produced myriad new technologies allowing for cleaner energy production and more efficient storage and transmission. Furthermore, the advent of computing and the arrival of the Internet of Things have resulted in numerous technologies that promise to improve grid efficient and cut costs for consumers.

Advances in clean power production have been largely focused on the development of reliable and efficient renewable energy resources. This paper briefly discusses the plummeting price of solar power and the need to implement wind power on a large scale. Particular attention is paid to the Cape Wind project and its promise to transform Cape Cod’s energy sector.

Physical improvements to the grid’s infrastructure should include a complete overhaul of the tangle of power lines crisscrossing the country. They are incredibly inefficient and only satisfactory for transporting power over short distances. The large-scale role out of renewable technologies will require the ability to effectively transport energy over thousands of miles from remote generation sites to urban consumers. Advances in transmission technologies have been slow – significant financial resources should be devoted to the development of high-temperature superconducting cables. The creation of cost-effective superconducting cables will revolutionize how the country distributes energy.

Beyond changing how the grid transmits energy, investments should be made in energy storage technologies, particularly in compressed air energy storage and lithium ion batteries. This paper examines how the electric vehicle market is driving innovation in lithium batteries, and how Tesla Motors is rebranding itself as an energy company positioned to provide lithium ion batteries on a grid scale. A brief discussion is given to how grid scale battery storage could move the United States to a decentralized power grid.

On a smaller scale, American homes need to embrace the Smart Grid – the Internet of Things promises substantial savings for the average consumer. Symbiotic relationships between computing and the grid could lower home heating bills while expanding the cloud-computing network. At the same time, the arrival of real time energy pricing could cause a paradigm shift in how consumers use power, smoothening demand throughout the day and reducing the burden of peak power on utilities. All these things are possible with the addition of computers to existing grid infrastructure.

Finally, this paper concludes by examining how to pay for the renovations the grid requires. Several different taxes, including traditional carbon taxes and novel power loss taxes, are examined. At the same time, the potential for climate bonds and the development of an independent power storage sector are examined. In all likelihood, a combination of methods will be necessary to finance an overhaul of the grid.

As the international community races to mitigate the impact of global warming, the United States can contribute by investing significant resources in the national power grid. Every aspect of the grid requires extensive updating to prepare the United States for the low-carbon economy. The cost of renovation will be substantial, but the returns will be even larger.

***Introduction***

 In the past two and half centuries, the Industrial Revolution has forever changed the course of history. During this time, humans exhibited profound ingenuity and remarkable creativity, developing and deploying technologies that transformed society. Simultaneously, the largest mass migration in human history occurred: people moved away from the countryside and into cities. In 2007, over 50% of the world’s population lived in an urban area for the first time in history.[[1]](#footnote-1) Combined, the Industrial Revolution and the movement to cities lifted hundreds of millions of families out of poverty. However, this transformation relied heavily on the use of carbon fuels, and in the process, humans impacted the planet on a scale never before achievable or imaginable.

 In the past several decades, researchers have amassed an incredible amount of scientific evidence demonstrating how the burning of fossil fuels has fundamentally changed the biosphere. The addition of carbon dioxide and other pollutants to the atmosphere exacerbated the green house effect, warming the planet 0.85**°** Celsius above pre-industrial levels.[[2]](#footnote-2) This increase in temperature has already changed ecosystems around the world, and experts now caution that 1 in 6 species may go extinct as a direct result of global warming.[[3]](#footnote-3) The future of our ecosystem is so uncertain, President Obama used his State of the Union Address to declare that “[no challenge] poses a greater threat to future generations than climate change.”[[4]](#footnote-4)

 As solid science continues to validate the existence and consequences of climate change, even the gas and oil industry have acknowledge the externalities of burning carbon fuel; last year, the CEO of Shell openly discussed “the real and current threat of climate change [and how] global companies like Shell have a responsibility to speak up.” [[5]](#footnote-5) The world is in agreement: a changing climate poses dire risks to future generations.

 With the planet already warming, the global community is finally discussing strategies to mitigate the impact of a warmer planet. Most experts agree the planet must be kept with 2° Celsius of warming to avoid catastrophic consequences and if the world keeps along at business as usual, dramatic warming is unavoidable – the Carbon Tracker Initiative estimates the world economy has already used 1/3 of the 2° Celsius carbon budget for the decades between 2000 and 2050.[[6]](#footnote-6) Fortunately, multiple agencies and institutions around the world have suggested ways to curb global warming. Unfortunately, there are no easy solutions. For instance, the International Energy Agency’s warns that energy related carbon dioxide emissions must fall by more than 50 percent by the year 2050. This is difficult enough to accomplish, but even then, the IEA predicts only an 80% chance of keeping global temperature increases under 2° Celsius.[[7]](#footnote-7)

 Fundamentally, if the world is to confront the challenge of climate change, massive financial and human capital investments are necessary. In the widely cited report *The Clean Trillion*, analyst Reid Capalino calls for investing USD 1 trillion per year over the next three and half decades to avoid surpassing 2° Celsius of warming. This is quadruple the investments in clean technology in the year 2014, and will require substantial political and public support to become reality.[[8]](#footnote-8) Certainly investments will be spread across sectors, research, development, and deployment, but the question remains which investments offer the most sizable returns. The greatest returns can be expected from modernizing older technologies.

 The world isn’t what it used to be, but the power grid is.

The United States power grid is the largest interconnected machine in the world – containing over 450,000 miles of transmission cables the grid provides on demand power to every corner of the country.[[9]](#footnote-9) However, despite its massive scope, the grid has seen no significant renovations since its creation and largely relies on technologies developed following World War II. Since then, technology has advanced at a staggering rate and Moore’s law has proceeded almost unhindered; it is time for the grid to take advantage of the progress made in the past half century. First, the grid must undergo an energy production transformation – we must decrease our reliance on fossil fuels by expanding the role of renewable resources in power generation. Second, the grid must undergo a physical transformation – we must change how we transmit and store power. Finally, the grid must undergo a technological transformation – we must smarten the grid by incorporating computers and the internet. This three-pronged approach will revolutionize the grid and prepare America for the low-carbon economy.

***Renewable Energy***

The first step the United States must take in modernizing the grid is increasing the amount of electricity produced by renewable sources. Currently, the burning of fossil fuels for power is one the greatest contributors to global warming, releasing over 23 trillion tons of carbon dioxide annually. This is over 700 tons per second.[[10]](#footnote-10) With coal accounting for the vast majority of fuel burned, it is clear the United States must explore other options to meet its energy needs. While critics berate renewable energy technologies as insufficient to power the country, wind and solar generation enjoyed enormous advances in the past two decades that have made them viable alternatives to traditional power plants. Both technologies are approaching parity with other sources and should be rapidly implemented, on a nation wide scale, to reduce the American dependence on fossil fuels. Other renovations to the grid will be largely meaningless if the United States does not change how it *produces* the energy the grid distributes.

***Solar Power & SunEdison***

Solar power has a long tradition in the United States but has only recently started to see widespread adoption. Historically, the price of solar was too high to compete with coal burning power plants and other renewable energy sources, specifically hydro power. However, over the past 20 years (and in the past five years in particular) advances in photovoltaic panels have dramatically reduced the price per kilowatt-hour (kWh) of solar produced energy. According to the Natural Resource Defense Council, the price of solar nationwide now ranges between 12 – 30 cents per kWh.[[11]](#footnote-11) These prices make solar power competitive with other sources of electricity – the nationwide price of power was 12.35 cents per kWh in March 2015.[[12]](#footnote-12) Unfortunately, despite declining cost, solar technologies produce less than 1% of the nation’s power.[[13]](#footnote-13)

 As government subsidies for solar technologies run out, the United States will need to rely on private companies to achieve widespread solar deployment. Already, a number of companies have sought to capitalize on the potential returns of going solar. Perhaps most notably, SunEdison has turned an initial interest in solar into a USD 8 billion renewable energy powerhouse – its recent purchase of First Wind makes it the largest developer of renewable power in the world.[[14]](#footnote-14) To achieve meaningful and widespread adoption of solar, others in the private sector must recognize the potential profit to be made in the solar industry. The government should continue to subsidize solar to help keep the market competitive, while the success of companies such as SunEdison needs to be more widely covered by financial journals.

***Wind Power & Cape Wind***

 As the United States embraces low carbon energy sources, it will need to diversify itself beyond solar power – solar has enjoyed disproportionate attention over the past several years because of dramatically falling costs, but wind power offers an alternative renewable energy source just as capable of meeting the nation’s energy demands. Sadly, conventional wind power has faced significant challenges acquiring zoning approval: residents frequently complain of the incursion of wind turbines on landscapes. This being said, offshore wind power is an alternative to conventional wind sources, and has an estimated total capacity of 4.2 gigawatts.[[15]](#footnote-15) While there are currently no active offshore wind farms in the United States, there are 14 projects in advanced stages around the country, and the technology has been proven in Europe.[[16]](#footnote-16)

 One such project under development is Cape Wind, a Cape Cod based ventured set to become the United States’ first offshore wind farm. The project was first proposed in 2001 and has gone through over a decade of planning, zoning, and development. With an initial life expectancy of 28 years, the 130 turbine wind farm will have an average output of 174 megawatts, or enough to meet roughly 75% of the energy needs of Cape Cod and the islands of Martha’s Vineyard and Nantucket.[[17]](#footnote-17) This is the same amount of energy produced in the burning of 570,000 tons of coal, 113 million gallons of oil, or 10 billion cubic feet of natural gas. Fundamentally, its operation will help bring Cape Cods energy sector in line with the area’s other practices of nature conservation and environmental activism. Furthermore, once the installation process begins in the early months of 2015, the project is expected to bring 1,000 construction jobs to the Cape, and upon its completion, it is expected that 150 people will be employed in its day-to-day operation. It is clear the project makes both environmental and economic sense for the people of Cape Cod and hopefully it will serve as a model for other communities looking to reduce their ecological footprint.[[18]](#footnote-18)

***Physical Grid Improvements: Changing Transmission & Improving Storage***

 Despite the progress made in renewable technologies in the past decades, the intermittency problem has hindered their widespread deployment. The intermittency problem refers to the inherent unpredictability of renewable resources – the sun is not always shining, the wind is not always blowing. However, a physical transformation of the national grid could alleviate this problem. Specifically, to achieve widespread adoption of renewable technologies, the grid must change the way it transmits and stores power. The physical footprint of the grid has seen few renovations since its creation, and modernizing the grid’s infrastructure has the potential for enormous returns.

***Improving Transmission & Eliminating Losses***

One solution to the intermittency problem facing renewable resources is the creation of a truly national grid. Currently, the grid is powered by thousands of individual coal power plants producing electricity for *local* customers. Conversely, renewable energy resources will work best when the grid is able to produce power in one area and deploy it hundreds, if not thousands, of miles away. In such a system, an energy economy will develop in which certain areas of the country are energy exporters and other importers. For instance, the South West could harness its solar power potential to export to the rest of the country. In addition, a nation wide grid could have dramatic benefits for wind power – the wind is always blowing *somewhere* and many papers have demonstrated that a nationwide network of wind turbines, either out at sea or across the country, can provide an incredibly reliable and steady power supply.[[19]](#footnote-19)

 To create a new national grid capable of transmitting power across the country, new technologies must be deployed to minimize losses in transmission cables – at present, an estimated 7% of generated power is lost in transmission.[[20]](#footnote-20) This may seem insignificant, but given the over 16,000 traditional power plants in America, these losses are equivalent to more than 1,000 power plants operating at full capacity but not distributing the power. Losses are magnified by distance, so to create a truly national grid, new technologies will need to be harnessed to limit the losses in transcontinental power transmission. While a transition to direct current transmission cables could eliminate losses on a local scale, the grid needs the development of superconductors to see a meaningful improvement.[[21]](#footnote-21)

Since their discovery in the early 20th century, superconductors have been an active area of research. Fundamentally, a superconductor is a material in which electric current experiences no resistive losses. [[22]](#footnote-22) This incredible property, long thought impossible, makes superconductors a dream of utilities around the world. Several small-scale networks have been installed, most notably at Jeju Island in South Korea: in October 2014, a 500 meter long cable demonstrated the ability of superconductors to transmit 150 times the energy of a comparable copper cable.[[23]](#footnote-23) For perspective, this means 4 superconducting cables could handle all the power generated by the massive Three Gorges Dam in China.[[24]](#footnote-24) Unfortunately, the technology has seen limited deployment because the only known superconductors exist at a few tens of Kelvins above absolute zero making cooling costs prohibitively expensive.[[25]](#footnote-25)

 Research into superconductivity and low temperature cooling has the potential for enormous returns on investment, both for financiers and society in general. The creation of large-scale superconducting cables would allow for renewable energy produced in one part of the country to be consumed in another, greatly alleviating the intermittency problem facing renewable power sources. Furthermore, even if the country does not deploy green power sources on a nationwide scale, the implementation of zero loss cables would reduce the total generated power needed to light American cities, a laudable goal in an off itself.

***Energy Storage***

While superconductors may be a decade or so from widespread adoption, one upgrade to the grid that is possible now, and has the ability to radically transform the use of renewable electricity, is energy storage. Currently, the United States has a nominal energy storage capacity of 24.6 gigawatts, or a measly 2.3% of total current output.[[26]](#footnote-26) This means when excess energy is produced in the grid, it goes to waste. This is in addition to the 7% losses discussed previously. Clearly, the United States needs to do a better job of utilizing the energy it produces; an improved transmission network is one part of the answer, power storage the other. Large scale storage will also mitigate the intermittency problem, as renewable energy generated during off-peak times can be stored for later use. However, any successful storage system must be on a grid-wide scale, and the technologies to accomplish this are just beginning to emerge.

***Mechanical Storage: Compressed Air***

Mechanical energy storage, despite its relatively limited use, has a long history in the United States and was first characterized by pumped hydro storage in which excess capacity was used to pump water uphill for later discharge. More recently, attention has focused on the implementation of compressed air energy storage (CAES).

CAES technology involves using excess capacity to compress air, normally in naturally occurring underground caverns. The pressure can be several atmospheres, and when extra power is needed, air is released through high-pressure turbines. CAES systems are designed for near instantaneous generation, meaning they can be used to modulate power throughout the day to meet peak usage. The single site currently in the United States is located in Alabama and uses an underground salt cavern to store the air. In the 20 years it has been in use, it has proven to be extremely reliable, and verified the viability of compressed air as storage system.[[27]](#footnote-27) The creation of other CAES systems around the country could significantly increase the nation’s total storage capacity.

***Chemical Storage: Lithium Batteries & Tesla Motors***

Mechanical energy storage never fulfilled its promise to change the energy economy, and given the geologic constraints of most systems, it seems unlikely it will become the main storage mechanism in the future. Instead, rapid advances in chemical energy storage have made batteries the darling of futurists. In particular, research into lithium ion battery technologies has seen significant advances as computers and smartphones became household appliances. Current lithium ion batteries are ten times cheaper than when first released, and yet hold twice as much energy.[[28]](#footnote-28) However, innovation in the sector is not finished; the electric vehicle market is quickly pushing the technology into the future.

The car manufacture at the forefront of battery technology is also the electric vehicle market’s most famous: Tesla Motors. The California based company of serial entrepreneur Elon Musk has made battery innovation a key aspect of its plan to capitalize the electric vehicle market. The company has committed sizable resources to battery engineering, and has invested an estimated USD 5 billion into the creation of the GigaFactory, a battery factory of unprecedented size located in the middle of Nevada. When opened in the coming year, the GigaFactory will produce cells with a total aggregate storage capacity of 35 million gigawatts. For comparison, this is equivalent to the entire global lithium battery output of 2013. Flooding the market will result in a drastic fall in price; while the exact magnitude is unknown, most experts believe the price per kWh of lithium storage will fall by a minimum of 30%.[[29]](#footnote-29) This price collapse will make lithium ion batteries a perfect opportunity to invest in grid storage.

With the price of batteries projected to be so low, the United States could embrace a decentralized energy system. Currently, the United States has a centralized grid where energy produced in a limited number of locations is then distributed to the farthest flung corners of the country. However, with the spread of solar technology and the proliferation of cheap and affordable home batteries, it will be possible for consumers to produce electricity during the day, store it in home battery systems, and then draw the power at night when they return from work. While this may seem utopic, Tesla Motors has unveiled a system called the Powerwall designed for such a future.[[30]](#footnote-30) Capitalizing on its advances in lithium technology, the carmaker is attempting to reposition itself as an energy company. While it will take time for the Powerwall, or other similar storage systems to become standard in American homes, rock star CEO Elon Musk (also chairman of SolarCity) has the charisma necessary to speed the transition along. More importantly, the technology could allow low-resource countries to leapfrog the developing world, and bring the low-carbon economy to resource-poor areas before other regions.[[31]](#footnote-31)

***Technological Grid Improvements: Benefits of the Smart Grid***

While the transition to a decentralized grid, or the development of superconducting cables, is likely to be slow, one step the country must take quickly is the implementation of the Smart Grid - microprocessors are becoming ever smaller and less expensive, and yet the largest machine in the world uses little computing power. The growing Internet of Things has attached computer chips to increasingly mundane items, and yet the substantial benefits to be gained from adding intelligence to the grid have only been superficially explored.

***Symbiotic Relationships: Nerdalize***

The phrase ‘Smart Grid’ has become increasingly ambiguous in recent years. However, this ambiguity is warranted as entrepreneurs have developed a wide array of technologies that embody the idea of using computers to improve the grid. A particularly unique example comes from Nerdalize, a company based in the Netherlands.[[32]](#footnote-32) Nerdalize is exploring how society can use the biggest by product of computing, heat, to reduce our dependence on fossil fuels.[[33]](#footnote-33)

Everyone is familiar with how much heat is generated from a single laptop, but most people do not realize the immense heat loads generated by industrial data centers. The cooling towers needed to mitigate this heat output consume tremendous amounts of electricity– in 2013 American data centers used 91 billion kWh, a large percentage of which was used to cool processors.[[34]](#footnote-34) Nerdalize has developed a technology that takes the heat from computing and uses it warm rooms. With this technology, Nerdalize envisions a vast cloud computing network spread out among consumer residences, with homeowners allowing Nerdalize to install servers in their homes in return for free heat. Such a system not only cuts the energy needed to cool computers, but also reduces the power necessary to heat homes. Such symbiotic relationships are only just beginning to be explored, but demonstrate the promise of the smart grid and the ingenuity of inventors around the world.

***Financial Returns: Motivating Consumers***

 The Smart Grid will be intimately linked to the home, and this is perhaps best exemplified by the growing popularity of the Google Nest Thermostat. The Nest is a smart thermostat requiring no programming or computer experience to operate; installation only requires replacing an old thermostat with the Nest. Its simplicity is its greatest attribute, and once installed, the Nest’s software learns the living patterns of the homes inhabitants. This is significant because most Americans do not realize the energy savings they can achieve by modulating their thermostats throughout the day. Turning down the heat while at work or while sleeping translates to significant power savings – Google claims the Nest can reduce the energy required to heat the average home by an astounding 20%.[[35]](#footnote-35) Of all the savings discussed so far in this paper, this is perhaps the most important because it *directly* impacts consumers. Consumers take action for personal benefits, and a 20% reduction in a home’s monthly heating bill is the kind of savings that motivates homeowners. In addition, Nest is another example of how how the Smart Grid is driving value creation (and will for years to come): Google purchased Nest for USD 3.2 billion in January 2014.[[36]](#footnote-36)

 Another way in which the Smart Grid will save consumers money is with the arrival of real time power pricing. As mentioned, power supply and demand is highly cyclical throughout the day, with peaks in the morning and evening. Along with these fluctuations comes variable pricing; the price of power can increase by an order of magnitude during peak usage. Many consumers are unaware of the variable price of power as they are charged flat rates that do not reflect the cyclical variations in price. The Smart Grid promises the advent of real time pricing in consumers settings, allowing consumers to make consumption decisions based on the actual price of power. Such a system has the ability to radically change the energy market, by shifting high energy tasks such dishwashing and clothes dying to those times of the day when electricity is cheaper. By shifting the demand for power, and not the supply, the advent of real time pricing promises to smoothen the demand for power and reduce peak power variability.

***Financing the Grid Revolution***

At this point, the benefits to reinvigorating the American grid have been broadly laid out, yet only the barest mention has been given to how to finance such a massive project. With a minimum USD 1 trillion needed in green investments over the coming decades to avoid disastrous warming, funding is in dire need.

***Carbon and Oil Taxes***

While unique financing methods may be needed, and will be discussed, there is no reason to believe that several traditional techniques would not be capable of raising the funding necessary to modernize the grid. First and foremost, a nationwide carbon tax would greatly increase the rate of grid updates. While such a tax seems unlikely to pass Congress in the near future, several studies have documented how a carbon tax is an effective way to promote efficiency. In addition, many companies have implemented their own internal carbon pricing schemes to great success. For instance, Disney instituted a carbon taxing system several years ago, and the company credits it as a driving force behind the business’s reduction in energy usage.[[37]](#footnote-37) Furthermore, raising the tax on oil and other fossil fuels, in particular natural gas, could serve as a significant source of revenue to finance the grid project. A carbon tax could also help deter the growing movement towards shale gas and oil. While shale gas and oil have drastically reduced energy prices in the past year, this fall in price should make the environmental community weary – high oil prices were a driving force behind the adoption of solar panels in the recent years. Regardless, these two taxes, proposed numerous times before, could help gather the funding necessary to rejuvenate the grid.

***Climate Bonds & Green Finance***

 Another possible avenue for financing renovations to the grid is green bonds. A relatively new instrument, Climate bonds have seen a proliferation of issuance in the past few years, reaching USD 35.59 billion in issuance in 2014.[[38]](#footnote-38) Fundamentally, a green bond is any bond whose proceeds are earmarked for the deployment of green technologies – this makes climate bonds well suited to finance clean grid improvements. In fact, several large banks have already issued climate bonds to fund projects related to renewable energy generation and the low-carbon economy. For example, Bank of America issued USD 600 million to finance green technologies, USD 40 million of which was used to install LED streetlights in Los Angeles.[[39]](#footnote-39) With the Climate Bonds Initiative predicting USD 100 billion in green bonds issuance in 2015, it seems reasonable to hope energy companies will issue bonds to fund grid renovations.[[40]](#footnote-40)

***Private Energy Storage***

At this point, I would like to propose two possible funding mechanisms I believe to be novel. Both are based on the need to use the energy produced around the country more efficiently and with fewer losses. The first deals specifically with renewable power and the issue of peak demand, namely that large quantities of green energy are generated off peak and go to waste, lost in the grid as heat. The drive to create batteries and a storage system designed to minimize these losses has been slow – traditionally is has been believed that only utility companies are capable of providing grid-wide transformations. However, I believe a private energy storage industry could prove self-sustaining. While subsidies may initially be necessary, I envision a situation where private companies develop the infrastructure necessary to implement grid-wide storage. This storage is then sold to utilities per kWh. This may seem strange, that utilities would pay to store their power, but as long as the price per kWh of storage is below the average price of power, utilities will be able to profit by then selling the energy in the grid when it is need. Through this system, the private sector provides the capital, funding, and innovation needed to achieve grid storage.

***Taxing Transmission Losses***

My second proposal to raise funds for the implementation of the Smart Grid requires a federal tax on power losses. With an excess of 7% of national power output lost to various causes (heat, resistance, excess supply), a 7% tax on losses (equivalent to the national gas tax at the time of writing), would generate an estimated 2 billion dollars in annual revenue. A direct tax on power losses would drive innovation and efficiency in the power sector while simultaneously raising the revenue necessary to renovate the grid.

***Conclusion and Review***

Society is reaching a critical juncture where steps must be taken to avoid catastrophic climate change. While debate continues to rage on about the best ways to prevent carbon emissions and curb global warming, it seems investment in the United States national power grid offers sizable returns. Through a combination of increasing renewable power generation, enhanced transmission and storage, and the implementation of the Smart Grid, America can once again become an environmental leader. Time is running out though, and action must be taken. The Grid Revolution *is* coming, and will transform the American energy sector for the next century.

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