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Economics & Practicality of the Large-Scale Implementation of Renewable & Clean Energy in the United States

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Abstract

The search for more efficient renewable and clean energies is one whose importance is constantly increasing. Especially as a nation with ample resources and potential, this issue is pertinent to the United States, which can use its vast geography to diversify its use of sustainable energy resources. The following discussion draws on and analyzes information from international energy-efficiency projects, as well as large-scale renewable installations in the United States. Specifically, reports on the United Kingdom's energy policy, the Empire Wind Project, the Oberon Solar Project, Pavegen, and more, are included. Wind, solar, wave, and nuclear energies, as well as their trade-offs, are explored, providing insight into the best approaches for mass implementation. Certain cases and projects involving each energy type are analyzed, and piezoelectric & AI technologies are considered for future construction to add marginal amounts of energy optimization to power grids. With all this information taken into account, economics and politics are considered for the best climates and conditions in which to put various types of clean and renewable energies, as well as which are better to focus on.

Introduction

When exploring the expansion of sustainable energy, several key factors must be considered. The type of energy used in a certain location is vital to ensure that costs are the lowest for the highest energy output, especially since renewable energies have higher costs for equal production levels compared to oil and other non-renewable energy resources. When considering what renewables are efficient, net energy is examined, which takes into account the energy required in all processes related to the construction, operation, and deconstruction of the units of an energy source. A high net energy means that a lower energy cost (mining, building, etc.) produces a higher energy product, in terms of the energy outputted by the source.

When determining the best energy resources, it is additionally important to note how the materials involved are disposed of after they have reached the end of their efficient lifespan. Efficient energy sources eliminate the amount of energy wasted in production, improving not only the reliability and output of power grids but also the amount of energy that can be utilized. Installation quantity must also be considered to maximize benefits by halting production once the additional costs exceed the additional benefits of making the installation. Aside from the economics aspect, policies and the general public can affect the success of energy resources like nuclear energy, and various specific conditions must be considered for each type.

United Kingdom's Plans

The United Kingdom is widely seen as displaying a 'green effort' through its climate policy, specifically

its plans to reach net-zero emissions by the year 2050. Its government's Action Plan states that analyzing and tracking the UK's power grid system, including its generation, transmission efficiency, and distribution, will help the country accomplish its first task in the plan of achieving a 100% clean energy grid by 2030. The idea of 'smart demand,' adjusting energy output according to the population's immediate demand, is becoming a bigger goal in an attempt to improve grid reliability. The government's final energy breakdown goal is "43-50 GW of offshore wind, 27-29 GW of onshore wind, and 45-47 GW of solar power, significantly reducing our fossil-fuel dependency. These will be complemented by flexible capacity, including 23-27 GW of battery capacity, 4-6 GW of long-duration energy storage, and development of flexibility technologies including gas carbon capture utilisation & storage, hydrogen, and substantial opportunity for consumer-led flexibility" (*Clean Power*, 2024). However, the project has been seen as spontaneous, with some unrealistic goals. An energy system that depends nearly completely on renewables and cleaner energy sources can reduce the dependability of the power grid, requiring long-term solutions that will be addressed later.

United States' Current Renewable Energy Projects

Empire Wind

One project with similar goals in the United States is New York's Empire Wind Project, which has the final goal of installing an offshore wind farm capable of generating around 2,070 megawatts of electricity, enough to power hundreds of thousands of homes. Empire Wind 1, the first planned phase of the project, consists of 54 turbines that have been installed around 20 miles southeast of the Long Island Coast. The overall output of this section of the project is expected to be 810 megawatts, and the initial power generation is planned to take place at the end of 2026.

The United States generates around 1,300 watt-hours of wind energy per capita, which ranks it relatively high on the global scale. However, with projects like Empire Wind, there are some trade-offs. For example, because many large wind farms are located in remote areas, maintenance costs tend to be high. Wind energy, though efficient in generation and productive of high net energy, has reliability issues because there is no guarantee of wind presence at any given time; this begs the need for battery stations to store excess energy in case of inconsistent wind, which are costly and add to the high upfront costs of wind farms. Additionally, in order to reduce the fluctuation in turbine output, changes must be made in mechanics like gear ratios inside turbines. Designing larger turbines, with larger gears that require fewer revolutions for equal output, would be more productive of operational energy, but this design presents its own issues; single gears can wear out quicker, and the size of these turbines would not be practical to implement in many places. Empire Wind has also been a prime example of the large construction costs associated with wind energy; although it "represents a significant milestone in the U.S. renewable energy sector[,] Empire Wind's financial stakes are substantial, with a gross book value of approximately $2.5 billion as of March 31, 2025, including $1.5 billion in project finance term loans" (*Equinor Reports*, 2025). These costs have slowed the project's progress and have significantly altered its original plans. Empire Wind 2, the second phase of the project, is now unlikely to be built, as agreed upon by its offtakers, BP and Equinor. Projects like Empire Wind are certainly feasible, but are initially expensive to build and require variety in build types depending on geography. With developments in maintenance issues and optimization of single-gear turbines, long-term costs can be reduced, making wind power a smarter choice.

Oberon Solar Project

In California, the Oberon Solar Project, located east of Los Angeles in Desert Center, currently consists of a 500 MW solar power plant that can generate enough electricity for 207,000 homes. Outlined in the project's development plan, the farm was intentionally placed "on relatively flat, contiguous lands receiving high solar insolation, that are in close proximity to established utility corridors, existing transmission lines with available capacity to facilitate interconnection, and road access" (*Oberon Renewable*, 2022). This specific decision mitigates one of the primary disadvantages experienced with solar energy, which is the high cost of connecting solar farms to existing power grids. Making the farm more accessible additionally decreases maintenance costs. To ensure minimum environmental impact, the project is planned to be taken down as soon as its useful life is over, which does not have a concrete time, though the project is expected to be efficient for at least 50 years.

Although the development plan for Oberon has certainly anticipated problems associated with large-scale solar energy projects, there are still downsides to the project, and notable downsides to solar energy in general that still apply. While Oberon was able to decrease construction costs, overall costs were still high; regardless of being able to connect the farm to already-built systems, the battery energy storage system (BESS) was still very expensive, as is the case with most large-scale solar projects. Like wind energy, another inconvenience with solar energy exhibited by Oberon is its dependence on weather conditions, and there is no guarantee that the BESS will be able to provide necessary power while the farm is inoperable. Additional costs that come with Oberon's geographical placement are the maintenance of weeds and other vegetation to ensure that the solar panels aren't blocked from full efficiency, as well as the extra water used in the farm's quarterly panel washes. The project is still environmentally mindful, however, as wildlife-friendly fences have been installed to allow wildlife like desert tortoises safe, necessary passage through specific areas of the project, reducing overall habitat impact.

Opportunities for Innovation and Expansion

Wave Energy

According to the United States Energy Information Administration, there are no commercially active wave power plants currently operating in the US. Wave energy is generated by harnessing kinetic energy from the constant harmonic motion of waves. So far, it does not have much history, but the European Union has done work in the field. It is one of the multiple forms of energy that aren't wind and solar that the EU has decided to undertake to "achieve the target of… 20% of [its] total energy consumption… [being] made up of renewable energy" (Astariz & Iglesias, 2015). Wave power has the potential for vast amounts of energy production, with ~17 terawatt-hours of potential power in the oceans. Unfortunately, however, wave power is predicted to be uneconomical in the short run. Many of these issues occur in areas like the manufacturing process, and it is possible to reduce the construction footprint of wave energy converters (WECs), decreasing their carbon and energy payback periods. Specifically, in a life-cycle assessment conducted by Andreas Uihlein, it was found that the actual assembly and installation of these systems have a nearly negligible environmental impact, as does the transportation required for the WECs (assuming a transportation distance of 1,000 kilometers for sub-components). The primary environmental effects are "closely linked to the material inputs for mooring, foundations, and structural components" (Bruno). There have been lower maintenance costs with wave power plants compared to other forms of renewable energy, justifying the short-term costs with energy payback and little wear.

There is an important distinction between hydropower and wave energy; hydropower involves

infrastructure like dams that harness water flow, whereas wave power plants specifically take advantage of waves' consistent bobbing. Both are consistently viewed with optimism as a growing source of renewable energy in the long term as there is much energy potential in the areas where they can be installed, and their reliability makes them an important source of grid stability. The plants' effective lives are much longer than other forms of clean energy and, as stated earlier, will allow them to eventually pay back their energy costs with a large part of their efficient lives left; specifically, hydropower plants can last around 65-85 years, whereas wind turbines and solar panels generally last around 20-30 years. Aside from the associated optimization challenges, marine dynamics are another issue to be considered with wave energy. The highest average wave power occurs between about 30 and 60 degrees north and south, but in these regions also exist delicate marine ecosystems that may be subject to drastic change with the large-scale implementation of wave energy, as some have already been displaced by dams and WEC anchors for moored ships. Such issues remain tasks to be addressed through collaboration with wildlife and conservation organizations.

Nuclear Energy

One of the forms of energy, although not renewable, arguably least understood by the public, is nuclear energy. The United States Department of Energy states that nuclear power plants currently help power 28 states and are "the largest source of clean power in the United States" (*Advantages and Challenges*, 2024). Specifically, nuclear energy makes up almost half of the United States' renewable energy production. It is produced indirectly by the process of nuclear fission, primarily involving Uranium, during which a neutron is fired at atoms in a reactor. When an atom is hit, it breaks up, or fissions, into two atoms and some neutrons, and those neutrons are shot towards other atoms in the same way as the original neutron. This chain reaction releases large amounts of heat energy, which is then used to heat water whose steam spins a turbine, generating the energy. The plants have systems to control the fission rate as needed and work rather reliably, opposing their generally dangerous perception. Like wave energy, nuclear power plants can operate all hours of the day, and their efficiency does not depend on variable conditions like weather, which can increase power grid dependability. Nuclear energy is quite efficient because of the small amounts of uranium that output large amounts of energy compared to equal inputs of material involved in other forms of energy. It is also far more prevalent on Earth than is generally thought. For example, the United States relies on nuclear power plants for around 20% of its electricity generation, and France, in its goal of "breaking its dependence on foreign oil…is home to 56 operating reactors and…relies on nuclear power for 70% of its electricity" (Igini, 2023).

While the negative public view of nuclear energy is generally overdone, there is still validity to such opinions. Nuclear power plants, while stable during operation, can be susceptible to acts of terrorism, and any accidents that do happen are likely to be quite serious. So far, there have only been three major accidents in the history of nuclear energy, two of which have not directly caused any deaths. Still, the displacement of hundreds of thousands of people in the surrounding areas is a notable inconvenience and encourages future plants to be built as far as possible from existing communities to limit the need for unnecessary evacuation protocols. Certain peace policies like the 1970 Treaty on the Non-Proliferation of Nuclear Weapons were enacted to both prevent future stockpiling of nuclear weapons and promote peaceful uses of nuclear power: specifically, clean, reliable, and efficient energy production. There is additionally the problem with nuclear waste, whose radioactivity begs the need for viable permanent storage solutions, which have yet to be created. Currently, nuclear waste is held in permanent above-

ground storage facilities, but these are running out of room, and building more would be quite costly. One permanent solution being investigated by many countries is deep geological disposal, which involves boring deep holes into underground rock formations to store the radioactive waste, where it can complete its decay before being safely removed.

Like other forms of clean energy, nuclear power plants are infamous for having expensive, lengthy builds that often do not go as planned and can require frequent maintenance. For example, Georgia's Vogtle Nuclear Power Plant, the largest nuclear plant in the United States, has had many construction issues that have cost the project billions of dollars and delayed it by years. In contrast to other energy forms being discussed, one disadvantage of nuclear energy is that it is not renewable. Because uranium can be difficult to acquire, it is also energy-intensive to mine the resources necessary to sustain the plants. However, "[t]he used fuel which comes out of the reactor can be managed in different ways, including recycling for energy production or direct disposal. As a matter of fact, many countries have been using recycled fuel for decades to partially fuel their reactors" (*How Does*, n.d.). Nuclear plants are generally expected to last at least 60 years which, as discussed earlier, is longer than the lifespan of machinery involved in other forms of energy. When considering large-scale implementation, this means nuclear energy can certainly be expanded if plant location, corruption and public confidence issues come closer to being solved.

Piezoelectric Technology

With the emergence of marine technology, an important consideration is the other ways in which kinetic energy can be utilized; the broadest, seemingly most practical way to do this throughout the United States is through piezoelectric surfaces, which can be installed anywhere and do not depend on any conditions other than population density. Piezoelectric surfaces are those that, when pressure is applied, generate a small amount of electricity. Japan has been exploring this technology since 2008 and has since installed piezoelectric sidewalks in areas of high foot traffic, creating the ability to power billboards and streetlights throughout major cities. Like other renewables, it does have relatively high upfront costs, and on its own is not suitable for grid-scale implementations. However, it utilizes already-present foot traffic and, without any emissions, can provide energy to smaller systems in urban areas. California has current plans to design and develop a piezoelectric highway which, given enough use, "would yield a carbon dioxide reduction of 115 million metric tons annually in California." As the technology is still developing, it is unclear how maintenance will contribute to costs, but it is expected to be relatively expensive due to constant wear from sustained use. To anticipate and solve these issues, technologies like artificial intelligence are being developed specifically in this sector in order to track such wear and optimize system maintenance.

Role of Other Emerging Technologies

As with the United Kingdom's 'smart demand', the implementation of artificial intelligence will be crucial for the efficient allocation of resources and monitoring power grid use, ensuring that supply and demand are matched. Power grids can be sensitive to even small changes in countrywide activity, so ensuring that this activity is properly monitored and swiftly accounted for is a goal that AI can help achieve. Using AI is also important in increasing overall grid efficiency, as "up to 175 GW of additional transmission capacity could be unlocked in existing lines with the use of AI" (Paris). Aside from energy-industry-specific uses, its possible applications are numerous; it can be used to assist in the management of industry production, transportation operation, and factory robotic efficiency. However, like nuclear energy, one factor that prevents some cases of wide adoption of AI integration is the general public's lack of

knowledge on the topic. With innovation everywhere in today's world and accelerating rapidly, leveraging AI would be to the advantage to keep up with other advancing sectors. Even with possible environmental impacts it may have, such as water use, the anticipated improvement in energy and labor efficiency does in fact make up for them to a certain extent of implementation.

Discussion/Conclusion

This discussion on different forms of renewable and clean energy was meant to expand on all the possibilities of addressing the prevalent sustainability issues in today's world, as well as various economic and political aspects. There are many possible avenues to be explored, both with large-scale renewable projects and with the strategic use of people's everyday life processes.

Diversifying the types of energy used in different areas of the world is a worthwhile decision because of the economics and politics of the situation. Relying solely on nuclear power plants would not be practical because of the high costs and chance of potential dangers, and using too many costly forms of energy would cause unhealthy international interdependence from the third world. It is also stated that "the U.S. should lead by example and encourage poor countries to invest in safe renewable energy technology," meaning that a larger investment in classic renewables like wind and solar energy would benefit not only domestic power grids, but the international relations regarding second and third-world nations (*10 Cons*, n.d.). This does not mean, however, that it is ideal to switch to a completely renewable world because, not only would this put oil-rich nations at a heavy disadvantage, but it would also impose unnecessary costs for improved environmental health that may not be worth such costs. It is important to consider the practicality of every decision, no matter how small or large, that is made with the final goal of a healthier world in mind. Having an environmental strength seems to be a strategic plan for smaller nations, which can focus on developing those technologies to make their grids more efficient, but for nations with geological diversities like the United States, taking into account where all the different forms of energy thrive is certainly in the world's best interest. In short, it is best to conduct a deep analysis, regarding all materials and processes involved, to find the most efficient use of every resource while maintaining grid dependency. Such analyses will vary greatly between countries based on the monetary and natural resources available to them. In general, funding and policy changes seem to be the best ways to make the most effective and substantial change, as they remain constant as a worldwide issue with regards to sustainability. Increased funding will immensely accelerate progress as it directly deals with the characteristic upfront costs of renewable energy, and finding ways to get past policy barriers will help approach economic goals that should be constant. Overall, wind and solar energy seem to be the most scalable in the short run as they are relatively predictable and have been around long enough for major technological developments. Newly developed technologies and energy sources, which show some of the most potential, remain topics to be explored and implemented further through studying how to mitigate environmental harm and maximize benefits in the long run.

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