Design of a Long-Distance Energy Transmission System Using High-Voltage Direct Current to Improve Electric Grid Robustness for Renewable Energy
(Technical Topic)

Assessing the Effectiveness of a Centralized Organization Hierarchy in Implementing an Energy Grid Transformation
(STS Topic)

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By
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On my honor as a University student, I have neither given nor received unauthorized aid on this assignment as defined by the Honor Guidelines for Thesis-Related Assignments.

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Introduction

Electricity transmission through the grid remains one of the foundational infrastructure components in any nation because it aims to deliver reliable and accessible power to its citizens, but an increasing role of renewable energy forces us to reimagine the way we plug in. Designs for the electricity grid emerged in the late 1870s when Edison was able to light up parts of Manhattan through his system of direct current (DC) transmission (Alassi et al., 2019, p. 530). Since then, designers with the vision to increase the accessibility of electricity have proposed different technologies to improve the range and efficiency of energy transmission. Most notably, Nikola Tesla championed the alternating current (AC) system, which was in stark contrast to Edison's DC power transfer design.

Tesla's proposal eventually won out because of the technical advantage of stepping up and down AC voltages more easily at the time. These high-voltage alternating current (HVAC) systems took center stage for energy development, beginning with the first long-distance power transmission line built between Niagra Falls and Buffalo, NY in 1896 (Nudell et al., 2019, p. 2). Infrastructure for more power lines matched the growth of coal and gas-fired power plants across the country, making electricity available to a greater fraction of the U.S. population (Shwartz, 2019, par. 4). Competition between utility companies who built out this infrastructure combined with federal regulation created natural monopolies of regional operators who were responsible for electricity transmission in their area. This organizational structure for electricity transmission gave way to the current national grid system: a patchwork of regional utilities that have their own power generation and distribution system, using HVAC to deliver electricity to their customers.

The technical and organizational developments of the grid can be mapped to the cultural value of having reliable access to electricity. While that value still holds today, an increasing concern about how that electricity is produced calls into question the current grid infrastructure's suitability for future energy generation methods. The U.S. grid was “largely built to accommodate coal and gas plants”, which are stable energy plants that could be built near high-population areas to mitigate the need for long-distance power transmission (Popovich and Plumer, 2023, par. 4). However, a growing cultural emphasis on sustainable energy sources is motivating the development of renewable power plants, introducing a surplus of intermittent electricity that the current grid infrastructure cannot handle. This clean energy is often generated “far from cities and the existing grid”, and the current grid is unable to efficiently transfer that power to where it is needed (Popovich and Plumer, 2023, par. 6). Combined with a lack of an authoritative body in charge of national interconnection projects that makes long-distance power transfer projects difficult to pass, and the U.S. electricity transfer system shows serious incapability to handle the greater mix of renewable energy.

A grid that does not have robust, long-distance power transfer capability directly impedes the development of renewable energy plants, which in turn will hinder national decarbonization efforts (Popovich and Plumer, 2023, par. 16). This prospectus proposes a newer grid infrastructure that leverages novel technology in advanced conductors to make power transmission more robust in the context of the renewable energy transition. Additionally, this prospectus will assess the potential of a centralized organizational system (in contrast to the decentralized grid network) to implement long-distance interconnection projects that could facilitate renewable energy growth.

Technical Topic: Design of a Long-Distance Energy Transmission System Using High-Voltage Direct Current to Improve Electric Grid Robustness for Renewable Energy

Even though direct current (DC) lost the battle to become the standard mode of electrical transmission to alternating current (AC), technological developments in the way high-voltage direct current (HVDC) can be controlled call for the reassessment of this technical actor in the renewable energy grid system. High-voltage alternating current (HVAC) had the edge initially when long-distance transmission was becoming a cultural value primarily because of the "early development of AC transformers that allowed for high voltage AC transmission for longer distances and lower losses" (Alassi et al., 2019, p. 530). Even though most devices still use direct current, meaning the alternating current coming out of the outlet needs to be converted, the significant advantage offered by transformers made this conversion worth it.

Figure 1 below indicates the key transformer actor critical in making long-distance transmission possible. Transformers change the voltage between electrical lines, which is relevant because increasing the voltages allows more power transfer with less line loss. Transformers can only work with AC because the alternating current creates the magnetic flux needed for the transformer to function, a capability DC does not have. These transformer components are what underly substations and power distribution facilities in the transmission chain, stepping up electricity generated at the power plant to high voltage that is sent to regional distribution centers where the electricity is then stepped back down to safe, residential levels (Halper, 2024, par. 15).

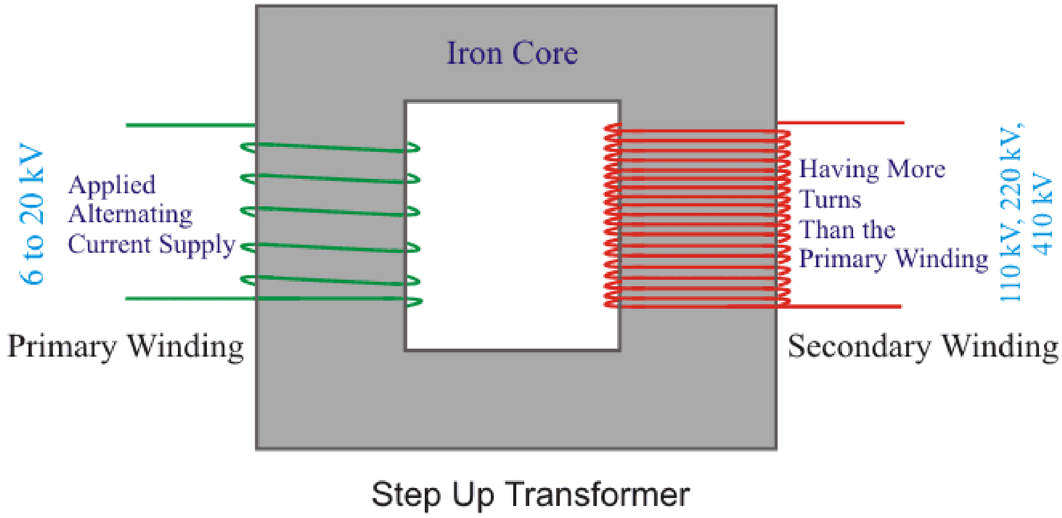

Figure 1. Image of a transformer with the primary coil (on the left) and the secondary coil (on the right). Magnetic flux is constant in the coils, so the voltage in the secondary (which has higher turns) is greater than the voltage in the primary by a factor of N_2/N_1, the ratio of the two windings, as noted by Faraday's Law (Alassi et al., 2019, p. 534)

HVAC works well for moderate distances, but, over very long distances (the kind that separates solar farms in Arizona to demand centers in New York), the lines become more inefficient than HVDC transmission. The main reason for the loss in AC efficiency over very long distances (more than 800 km) as illustrated in Figure 2 below is capacitive and reactive charging effects, which are features exclusive to AC. The challenge for HVDC earlier on was the lack of electrical components that could handle and redirect the HVDC; in other words, there was no efficient transformer equivalent for DC. However, the creation of thyristors in the 1960s and insulated-gate bipolar transistors (IGBTs) in the 1980s made the HVDC technology viable on a grid scale, leading to improvements in the breakeven distance (Nudel et al., 2019, p. 5). These technical actors are significant because DC does not have the capacitive and inductive losses that build up over very long distances, meaning HVDC is an attractive method for the long-distance interconnection infrastructure needed to connect remote renewables to the grid.

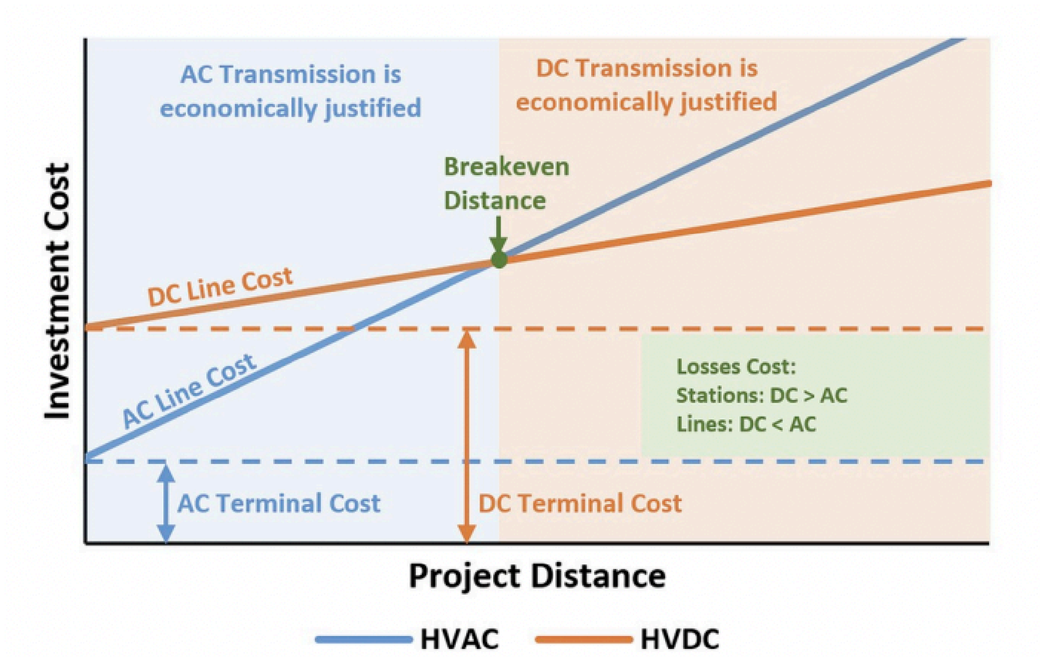

Figure 2. Comparison of the economic viability of HVAC and HVDC lines over various distances. HVAC has proved viability for the moderate distances required by coal and natural gas-fired power plants, but renewable plants, which do not have the luxury of placement near demand centers, require very long distances (Alassi et al., 2019, p. 532).

HVDC is not intended to replace HVAC; instead, the two modes of transmission can work in harmony. HVAC is better for local transmission, while HVDC is now viable for transnational interconnection. Where these new HVDC lines should be placed is not entirely clear (Shwartz, 2019, par. 10), so my technical deliverable will be a proposal for the locations at which these new HVDC lines should be constructed in the near term to connect more potential renewable energy plants with the grid. My technical project will build on previous work predicting electrical grid upgrades and studies that assess where renewable energy plants should be developed to determine the most economical distribution of these HVDC lines (Department of Energy, 2023, “Key findings of the Needs Study”).

STS Topic: Assessing the Effectiveness of a Centralized Organization Hierarchy in Implementing an Energy Grid Transformation

The organizational structure of the grid plays just as important a role in determining system efficiency as the technical components. The U.S. electric grid is divided into three main sections (Eastern Interconnect, Western Interconnect, and Texas Interconnect) which are further divided into regional operators that often have competing interests (US EPA, 2022, par. 8). As mentioned earlier, these regional utilities were formed as a result of natural monopolies during grid infrastructure build-out in the 20th century when it was difficult to sustain traditional competitive markets given that the company with the largest infrastructure would dominate electricity distribution (Nudell et al., 2019, p. 4). The kinds of long-distance transmission projects that are necessary to increase the robustness of the grid to renewables “require the approval of multiple regional authorities”, and “there is no single entity in charge of organizing the grid” (Popovich and Plumer, 2023, par. 9-10).

Figure 3 illustrates projections of the magnitude of grid interconnections needed to reach clean energy goals in the next decade. Given the long distance between where the renewable energy is generated and the demand centers, technical improvements in power transfer alone will not be sufficient to develop the grid; organizational harmony is also required. One of the main reasons interconnection projects get shut down is due to the lack of approval of regional utilities along the way, which may deny a proposal for any number of reasons, from a disinclination to buy power from other markets to a desire to keep their local system from being overloaded with excess energy (Nudell et al., 2019, p. 6). This dissonance does not just affect transmission projects, but it also negatively impacts the viability of renewable energy plant proposals. According to Shao, there has been a surge in proposals for wind and solar projects, which, if built, would allow the U.S. to “hit 80 percent clean energy by 2030” (2022, par. 14-15). The cost of not having an upgraded grid system is that wait times for project approvals have doubled since the past decade, so most proposals either withdraw or get rejected, meaning a significant step back in reaching net-zero emission goals.

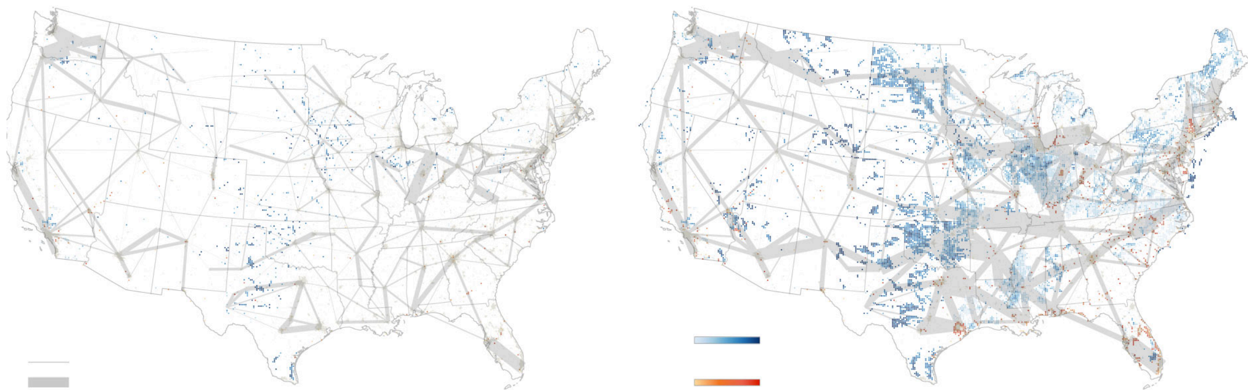

Figure 3. An illustration of the projected transmission network density needed in 2035 to reach goals of 100% clean electricity usage per National Renewable Energy Laboratory. The map on the left shows the state of the grid in 2020, and the map on the right shows the 2035 projection.

A centralized system has the potential to address the dissonance and backlog issues in the current organizational system. In fact, many other infrastructure systems in the U.S. have a centralized organization that begins with specific departments in the federal government. The electricity grid is an outlier when it comes to national resource distribution infrastructure. “It’s very different from how we do other types of national infrastructure,” said Michael Goggin, vice president at Grid Strategies, a consulting group. “Highways, gas, pipelines — all that is paid for and permitted at the federal level primarily” (Popovich and Plumer, 2023, par. 11). Federal subsidies are given to electricity operators for infrastructure development, but one issue is that these utilities spend the money on local development projects instead of the long-distance interconnections that have shown to be beneficial for renewable energy. As Popovich and Plumer note, “in recent decades, the country has hardly built any major high-voltage power lines that connect different grid regions" because while "utilities and grid operators now spend roughly $25 billion per year on transmission, much of that consists of local upgrades instead of long-distance lines that could import cheaper, cleaner power from farther away" (2023, par. 12). A central actor in charge of the system could oversee interregional projects better than local utilities, meaning a better usage of funds.

While a central actor for the grid system seems productive, it remains unclear how such an organizational structure would function in the U.S. My STS research aims to fill this gap in understanding by doing a case study on StateGrid, China's centralized grid operator, to reveal the practical implications of a centralized actor for the grid on transmission infrastructure. My study will build on both the previous work of independent researchers such as Nudell and others (2019) regarding the U.S. electricity market evolution along with studies of StateGrid's impact on China's integration of renewable energy to assess the ability of a centralized organization system to develop long-distance transmission projects. The main challenge will be mapping the motivations of the organizational actors involved, and I anticipate my deliverable will be a comparison between the two electricity markets and a recommendation of the utility of a centralized actor for the electricity grid in the U.S.

Conclusion

The anticipated deliverable of my technical work will be a design proposal for an HVDC system that is economically viable in the context of a growing mix of renewable energy. The anticipated deliverable of my STS research will be an assessment of the ability of a centralized organizational system in the U.S. to implement transmission infrastructure based on a rigorous study of China's StateGrid. If I can propose effective locations for the HVDC power system and show that it is possible for centralized efforts to implement this technology rapidly, then this would directly address the issue of renewable energy curtailment and increase the number of accepted proposals for clean energy production (Alassi et al., 2019, p. 547). This evolved system would avoid major losses in both cost and energy that are experienced today as a result of an undeveloped grid, and a transition to a fully sustainable energy mix would be significantly accelerated. (2194 words)

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