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Review

A comparison of the technological, economic, public policy, and environmental factors of HVDC and HVAC interregional transmission

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Abstract: The design of an interregional high-voltage transmission system in the US is a revolutionary technological concept that will likely play a significant role in the planning and operation of future electric power systems. Historically, the primary justification for building interregional high-voltage transmission lines in the US and around the world has been based on economic and reliability criteria. Today, the implementation renewable portfolio standards, carbon emission regulations, the improvements in the performance of power electronic systems, and unused benefits associated with capacity exchange during times of non-coincident peak demand, are driving the idea of designing an interregional high-voltage transmission system in the US. However, there exist challenges related to technical, economic, public policy, and environmental factors that hinder the implementation of such a complex infrastructure. The natural skepticism from many sectors of the society, in regards to how will the system be operated, how much will it cost, and the environmental impact that it could potentially create are among the most significant challenges to its rapid implementation. This publication aims at illustrating the technological, environmental, economic, and policy challenges that interregional HV transmission systems face today in the US, looking specifically at the Clean Line Rock Island project in Iowa.

Keywords: renewable energy; wind energy; transmission systems; HVDC; HVAC; energy policy; energy economics

1. Introduction

A combination of excellent wind resources, production tax credits, and an aggressive public policy has positioned the state of Iowa to be among the world leaders in wind energy production, with an estimated 27% of electricity generated by wind energy resources. Rough approximations suggest a total number of jobs both direct and related in Iowa are 3,000–4,000, ranking this state as second for number of wind energy related jobs in the US in 2013. Additional benefits include savings in water consumption of 3.4 billion gallons per year, and over 5.9 billion metric tons of CO_2 emissions reductions annually [1]. In market related processes, the development of new market mechanisms and the preliminary design of new market commodities, e.g. dispatchable intermittent resources and ramp rate products, suggest a decreasing trend of manual curtailment of wind generation in the Midcontinent Independent System Operator (MISO) footprint, as shown in Figure 1 [2,3,4]. Investments in wind generation are expected to continue, where the potential inland wind generation is more than 500 GW [5,6].

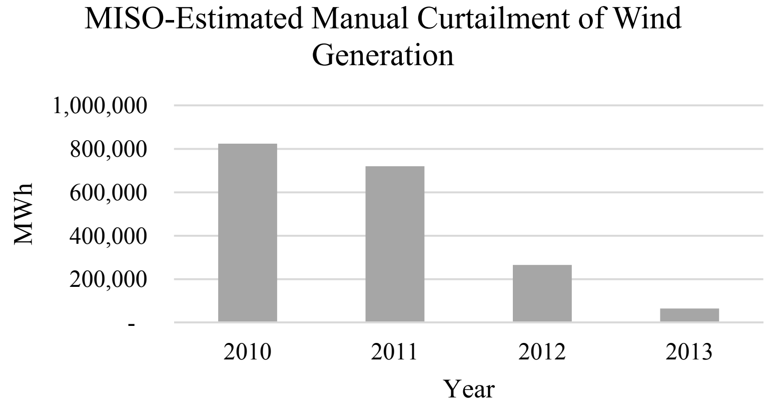

Figure 1. MISO-Estimated Manual Curtailment of Wind Generation since 2010 [4].

Overall, Iowa is addressing wind power implementation challenges in a rapid and efficient way. However, the value of achieving very high wind power generation is still uncertain if wind energy cannot be exported to distant load centers [7]. A general consensus is that the existing transmission infrastructure of the US will require additional capacity to accommodate higher penetration levels of wind generation, and achieve national renewable portfolio standard targets more efficiently. Most of these preliminary studies agreed on one thing: using interregional transmission is the most cost-effective way to achieve these goals [8–12].

In this publication, a discussion of the technological, economic, public policy, and environmental challenges associated with implementing interregional HV transmission systems in the US is presented. Section 2 presents the technological challenges associated with radial and meshed HV systems, the computational complexities of operating a large-scale interregional HV network, the issue of interoperability, and the challenges related to protection systems. In section 3, an economic comparison between particular HV transmission systems is presented. Section 4 discusses public policy challenges including externalities associated with implementing HV transmission infrastructures. Finally, in Section 5 an HV transmission project in Iowa is discussed in relation to the preceding sections within this publication.

2. Technological challenges of interregional transmission systems

Interconnection of electric power systems has proven to be an economic alternative that facilitates energy trading between different market structures while guaranteeing the reliability of the network [13]. Traditionally, the main drivers for building interregional high-voltage (HV) transmission lines have been to: provide additional capacity during extreme demand shortages, minimize congestion of transmission capacity, and enable the share of emergency reserves [14]. The preferred option, as discussed below, for this type of interconnection is based on a high-voltage direct current (HVDC) transmission line using a line commutated converter (LCC). The rest of this section focuses on multi-terminal HVDC networks, as it is consider to be a viable option for future electric network designs the US.

In recent years, additional benefits of HV transmission systems had been identified. These include: reduced capacity to meet future peak demand, reduced reserve capacity to manage variable generation, reduced curtailment from renewable generation resources, ease of maintenance, and simultaneous power exchange and trading between multiple regions separated by long distances using multi-terminal configurations [15]. In China, the first multi-terminal HV DC-AC hybrid network is expected to be in operation by the end of 2015 [15]. In the US, recent investigations have illustrated the value of multi-terminal networks at the interregional level [8,11].

HVDC systems can be classified in two general designs: series and parallel [16]. The latter can be further subdivided into point-to-point, or radial, and multi-terminal, or meshed, configurations. For point-to-point configurations, the LCC has been the preferred option to connect existing alternating current (AC) transmission systems with HVDC overlays, as presented in [16], and discussed in Section 3 of this publication. When considering a multi-terminal HV network, LCCs are limited in terms of performance and economics, mainly due to the need of additional equipment that must be installed to integrate multiple HVDC lines into a single converter station, substantially increasing the overnight investment cost of the project. Due to its control capabilities and better dynamic performance, the voltage source converter (VSC) is expected to be the ideal option for multi-terminal HVDC configurations. Additional benefits include: more operational flexibility than LCC, total control of real and reactive power, improved power quality, and smaller footprint of the converter station. Figure 2 shows a conceptual series-radial configuration, in which two regions are connected through an HV transmission line, and Figure 3 shows the meshed configuration, where multiple transmission zones can be connected using multi-terminal converters.

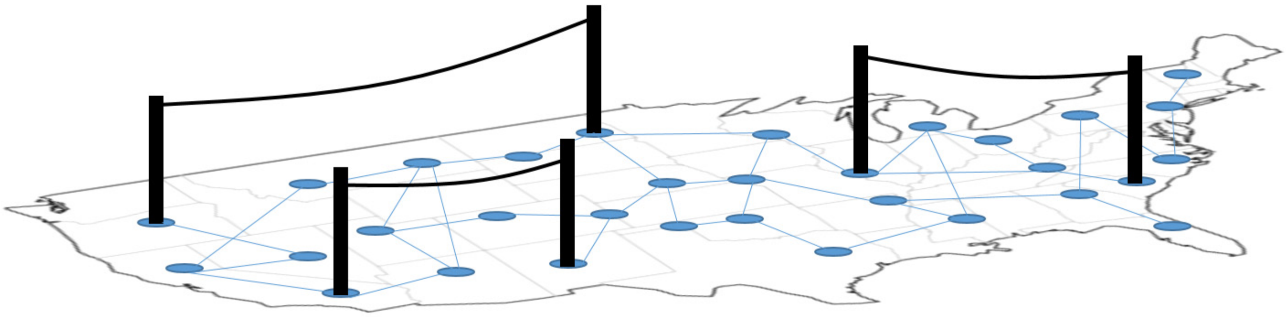

Figure 2. Conceptual HVDC Network Design: Point-to-point.

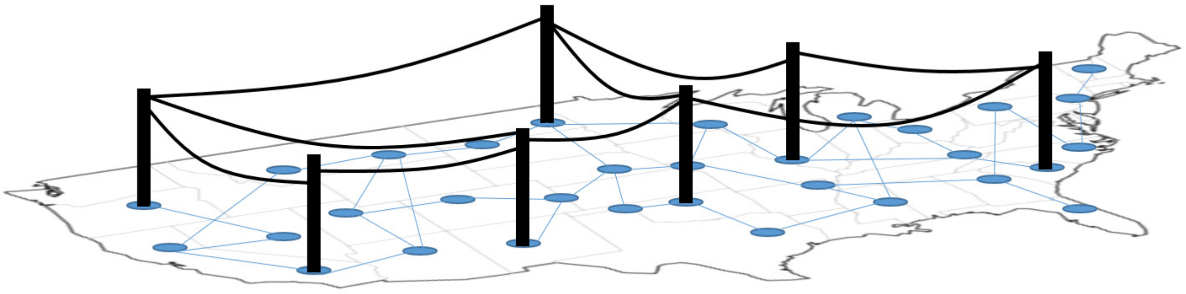

Figure 3. Conceptual HVDC System Design: Multi-terminal.

2.1.Challenges of multi-terminal HVDC networks

In contrast to point-to-point configurations, also referred to as radial configurations, modeling a multi-terminal HVDC system in real-time operations requires modifications to existing algorithms. Several authors have extended the analytical formulation of production cost programs (e.g., security-constrained economic dispatch and security-constrained unit commitment) to account for the interactions between HVDC overlays and the existing AC networks [15,17,18]. The objective function of a traditional production cost program minimizes the total cost of energy and ancillary services for all system nodes/converters N, as shown in equation (1),

$$Minimize\sum_{k=1}^{N} ce_k P_{\mathrm{i},k} + \sum_{k=1}^{N} cr_k P_{\mathrm{i},k}^{res} \tag{1}$$

where, ce_k represents the energy cost at node/converter k, P represents the power of generation unit i at node/converter k, cr_k represents the cost of reserve unit i, and P^{res} represents the reserve power of unit i at node/converter k. The simplified co-optimization of energy and ancillary services objective function is constrained by power flow equations, demand supply, unit commitment considerations, and reliability considerations. The general steady-state HVDC-AC power flow constraint is a set of non-linear algebraic equations at each node of the system, as shown in equation (2) [15].

$$\begin{aligned} P_{gi} &= \sum_{k=1}^{n_{ac}} V_{gi} V_k [\mathrm{G}_{ik} \cos(\theta_{gi} - \theta_k) + B_{gi} \sin(\theta_{gi} - \theta_k)] \\ Q_{gi} &= \sum_{k=1}^{n_{ac}} V_{gi} V_k [\mathrm{G}_{ik} \sin(\theta_{gi} - \theta_k) + B_{gi} \cos(\theta_{gi} - \theta_k)] \end{aligned} \tag{2}$$

For each node k of the network (k can be also defined as the point of common coupling between the i^{th} LCC or VSC station and the network), the real power P_{gi}, the reactive power Q_{gi}, the voltage magnitude V_{gi}, and the voltage phase angle θ_{gi} are to be calculated. A common practice is to use DC power flow equations to reduce the simulation time of large-scale networks. Assuming a linearized version of equation (2), the computational time can be approximated as the number of constraints squared. This might become an issue when contingencies related to the extended layer of multi-terminal HVDC transmission lines are added to the security-constraint optimal power flow model. Decomposition methods and computer parallelization might be a starting point for the development of efficient computer algorithms [19]. Even with the improvements in computational time, the issue of interoperability, which requires coordination between the different balancing areas, will still be a challenge for real-time implementations.

2.1. Interoperability

Perhaps one of the greatest challenges associated with HV interregional transmission systems is the coordination between the different independent system operators. The question of how will a multi-terminal HVDC network can facilitate the share of ancillary services is still unanswered. Several authors have proposed allocating participation factors to the multi-terminal HVDC converter stations, as it is done with automatic generation controls of generation units [20]. In a related work, a comparison was performed between centralized and decentralized control strategies, were a DC voltage control is distributed among different converters, and a participation factor is allocated to each converter based on market signals [21]. Analytical models have also been proposed to include droop control in power flow equations, as shown in equation (3) [15],

$$(V^{p}_{dc\_com})^2 - (V^{p*}_{dc})^2 + 4\beta_k\left(\frac{P^{*}_{gk}}{2} - P^{p}_{gk} + \beta_{fk}(f_s - f_k)\right) = 0 \tag{3}$$

Where, V_{dc_com} represents the common DC voltage feedback, and β_k represents the droop coefficient for the k^{th} converter. Real-time implementation of this concept is yet to be realized. Non-linear terms associated with the voltage control increases the computational complexities, and the coordination of droop control between different market structures is a regulatory challenge. Furthermore, a market process for sharing ancillary services in an interregional multi-terminal HVDC network does not exist.

2.2. HVDC protection systems

Another technical challenge of meshed HVDC systems is the capability of the protection system to interrupt non-sinusoidal electric current [22]. In conventional AC networks, the protective device (e.g. breaker) will disconnect an element from the system at the time when the sinusoidal wave reaches zero. This way, arcs are minimized and the capability of interruption is less. In contrast, HVDC systems cannot rely on zero-current crossing to interrupt high electric currents. An alternative option to address this problem is to use fast current control to mitigate fault currents and VSC based on full-bridge modules can provide this service without the need of a DC-breaker [23]. Also, differential protection schemes might be used to mitigate large drops in the HVDC line. Even with the existence of a commercial high-capacity HVDC breaker, the communication and coordination between converter stations is still a technological challenge. It should be noted, however, that ABB has reported progress in this area with the development of a DC protection system of their own [24].

3. Economics

3.1. Background

With any new or competing HV transmission technology, the choice of which design to implement generally boils down to an economic comparison. A new transmission system's investment cost can be separated into several different categories including but not limited to: substation costs, land use, cable costs, operational costs, construction costs, maintenance costs, and insurance costs. Four different transmission options will be discussed in this section. Data and figures were provided by Alberta Energy and are used in this paper with permission. When implementing a new HV transmission system the overall goal is to transmit electric power in the most economical way possible. [25]. HV transmission systems have many contributing factors that will have a direct impact on the overall cost structure. Some of these factors are: power capacity to be transmitted, the type of transmission medium, environmental conditions, safety measurements, and other regulatory requirements [26].

All transmission examples being considered in this paper have line lengths of 600 km. Using examples with relatively long transmission lines and a higher power capacity rationalizes investing in HVDC systems for these projects. Alberta Energy's Assessment of Electric Transmission Technologies [27] provides a background on each technology discussed in this section. Each option in this section is introduced non-technically. The goal of this section is to summarize transmission technology options for long distance projects (e.g., 600 km).

Costs in this section are given as an example only. For illustrative purposes this section summarizes 600 km power transmission schemes from the Alberta Case Study. Because the net cost savings of a DC-line over an AC-line increases with line length, any conclusion based on a 600-km line as evaluated in subsequent sections would validate the choice of DC over AC for the transmission line of longer length (such as the 800-km transmission line project as discussed in Section 5). Land costs are not included, which can greatly vary by area. Detailed planning studies are required to quantify the expected value of a transmission project.

3.2. Option 1: 2,000 MW Single Circuit HVAC Overhead Transmission Line 500 kV

Options 1 and 2 are HVAC technologies, whereas Options 3 and 4 are HVDC technologies. The transmission line for Option 1 consists of a 500 kV single circuit line with a power capacity of 2,000 MW. For the two HVAC technologies, only overhead lines are considered, because the prices estimated for construction of underground HVAC are extremely high. The estimated cost for the transmission line itself is $1.2M USD/km (converted from Canadian Dollars (CAD) to United States Dollars (USD), using a conversion rate of 0.91 USD/CAD).

A 500 kV substation was assumed to be at each end of the transmission line. Within this study the land costs were not taken into account for the substations. The estimated cost for the substation in Option 1 is $41.6M USD per substation. For longer lines a series compensation device is necessary in the middle of the transmission line. A total of three thyristor controlled series compensators were required at uniform intervals along the overhead line for Option 1. The estimated cost for 3 installations of this component for Option 1 is $64.3M USD [27]. Below, in Figure 4, a general price breakdown for technology Option 1 is displayed.

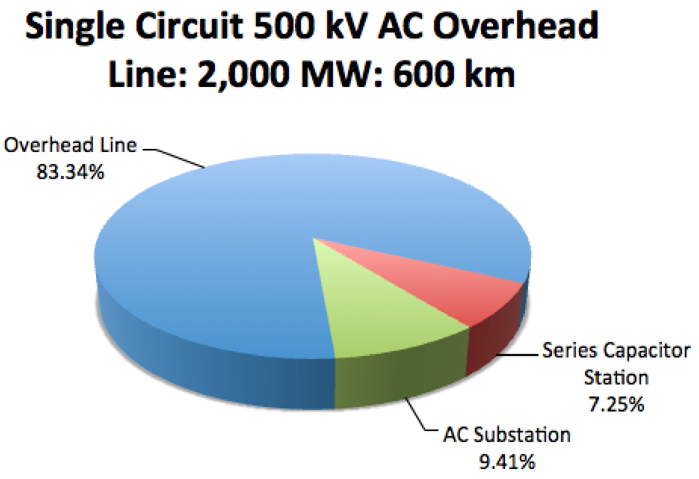

Figure 4. Option 1 cost breakdown.

3.3. Option 2: 4,000 MW Double Circuit HVAC Overhead Transmission Line 500 kV

Option 2 consists of a double circuit overhead line. Both circuits were installed on the same tower, which increased the transmission capacity two-fold. The right-of-way (ROW) used in Option 2 is slightly wider than a single circuit line, but also needs higher towers.

Option 2 required a larger substation that was nearly double in price of what was considered in Option 1 (power capacity was also doubled). The substation costs for Option 2 were estimated to be $83.2M USD. Below is a chart that provides a general price proportion breakdown for technology Option 2 [27].

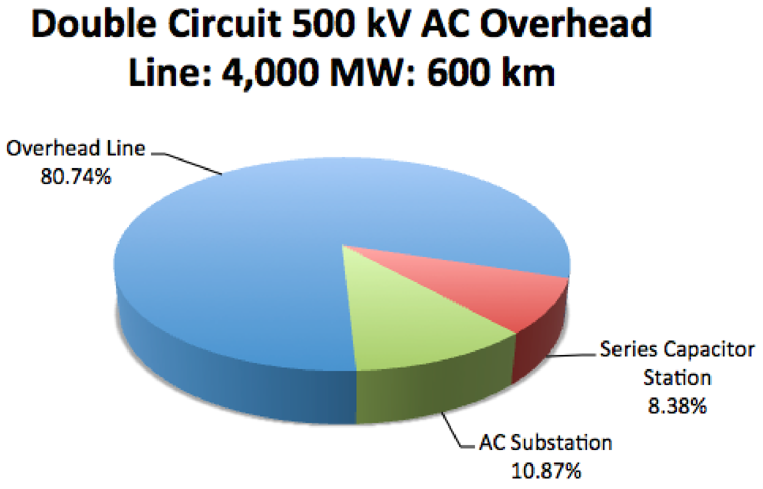

Figure 5. Option 2 cost breakdown.

3.4. HVDC Cost Background:

HVDC converter stations have a much higher cost than an HVAC substation. About 2/5 of the

HVDC converter costs were attributed to the AC switchyard and transformers (also needed in an HVAC substation). These costs are dependent on the line length. If the HVDC is a back-to-back installation, the converter costs heavily dominate. For example, if the HVDC line is longer (e.g. 2500 km) then the converter cost would account for a much smaller percentage [27].

Below is a popular figure that compares DC and AC transmission costs. Once the "break-even distance" is crossed, HVDC becomes a better financial option to transport electric energy. Siemens estimates the break-even distance in general to be between 500 and 800 km [28]. These longer distances for bulk power transmission are much better suited for HVDC technologies.

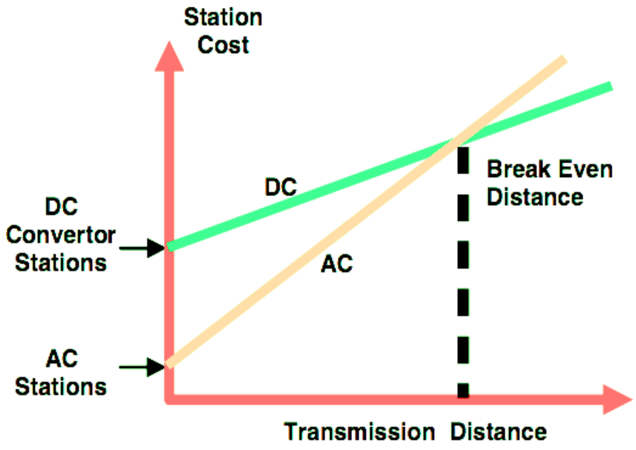

Figure 6. Cost comparison AC vs. DC Systems.

3.5. Option 3: 3,000 MW +/−500kV HVDC LCC Overhead Transmission Line

Engineering, procurement and construction costs (EPC) were estimated for Options 3 and 4. Under EPC contracts, contractors design each installation, procure all required materials, and build the project. Option 3 assumed a twin conductor bundle due to the complexity of analyzing a three-conductor bundle. The line for Option 3 has a capacity of 3,000 MW.

This HVDC line was constructed with a LCC. Several different facts should be stated for this technology option. The LCC option for HVDC is predominantly used when there is a need to move large amounts of power. Even though the costs are high for converter stations, they can be constructed in stages to reduce the initial cost of the project. Most importantly, the LCC technology for HVDC transmission has great control over power flow [27].

The estimated cost for the transmission line in option 3 is $0.7M USD/km. This is the highest cost component for Option 3. The second highest cost component for Option 3 is the LCC HVDC converter. For an overhead line (OHL) +/− 500 kV bipole scheme, the estimated price of the converter for a 3,000 MW system is $301.4M USD.

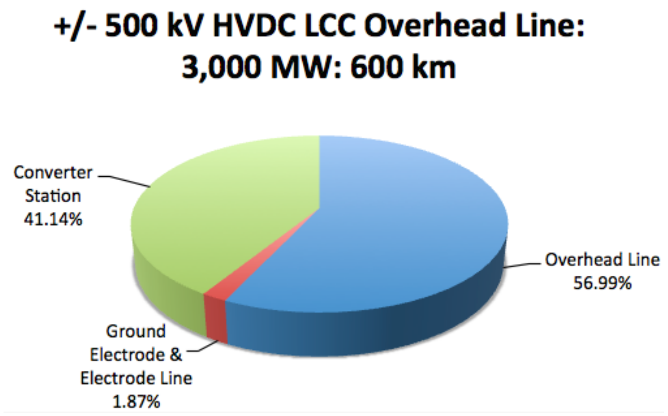

Figure 7. Option 3 Cost Breakdown.

3.6. Option 4: 2,000 MW +/−500 kV HVDC LCC Underground Transmission Line

The power capacity for Option 4 is 2,000 MW. The underground transmission cable is the highest cost component for this technology option. A 500 kV mass impregnated cable with a copper conductor of 2,000 mm^2 area was used for the cost estimate. The cable cost was estimated to be $0.74M USD/km (single conductor). The splice cost was estimated to be $0.06M USD/pc. The termination cost was estimated to be $0.3M USD/pc.

Several assumptions were made for this cost estimate. First, there were two-bipole cable lines installed to match the 2,000 MW converter. An individual line was assumed to have the capability of carrying up to 1,300 MW. During normal operating conditions, each line is capable of carrying 1,000 MW. Charging current was considered to be negligible for this option.

Next, the installation costs were the second highest cost component for Option 4. These costs were estimated to be $1.7M USD/km. The final cost component was related to the converter station. A 2,000 MW LCC HVDC cable scheme at the rated voltage was estimated to be $237.4M USD. Figure 9 illustrates the cost breakdown for all elements of Option 4. In this study, this option is not economically feasible due to the increase in cost added by the underground cable construction. Potential externality costs were not included, but will be discussed in Section 4 [27].

3.7. Economic Summary

The four options considered in this section are a representative subset of transmission considerations that could have been discussed. The point is to address the issue of transmission with numerical values in order to help mitigate the skepticism regarding transmission infrastructure. Public perception about technologies being proposed for a large-scale wind energy project may change if a plethora of knowledge, including actual cost figures is at the public's disposal.

Considering the main focus of this paper is a comparison of HVDC and HVAC transmission options, it is reasonable that a VSC based system may be considered as well. The VSC uses devices with turn-off capability. In particular they use insulated gate bipolar transistors (IGBT) that allow for much quicker switching ability. The disadvantage from a cost perspective when compared to an LCC technology is that the cost is about 50% higher for the converter. Moreover, the IGBT devices cannot withstand as much power, nor are they as robust as the thyristor technology. Additionally, VSCs are currently unable to clear temporary direct current line faults that have multiple and low voltage restarts for HVDC systems with overhead lines [27].

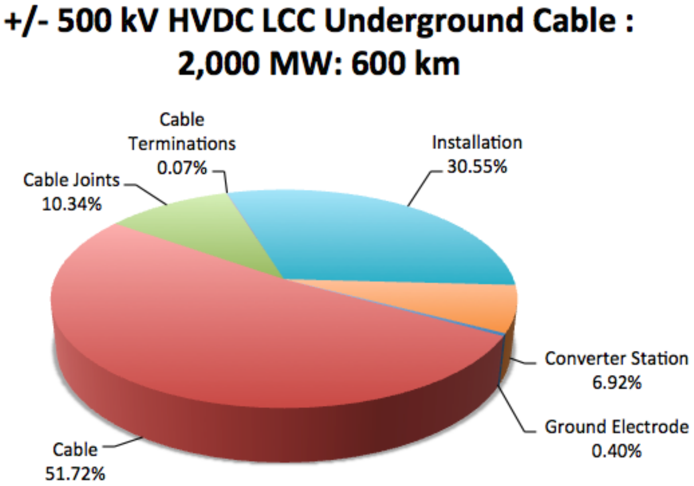

Figure 8. Option 4 cost breakdown.

The conclusion that can be drawn regarding the HVDC (Option 3) technology is that even though the overhead line cost is low, a bulk cost is added from the required (very large) converter stations. The transmission of bulk power for higher distances is best implemented with HVDC using LCC technology as opposed to the HVAC options discussed in this paper. Moreover, the right-of-way (ROW) for Option 3 is much less than HVAC options with the same capacity. The ROW numbers can be found in case studies 6 & 9 in Alberta Energy's Assessment of Electric Transmission Technologies. Figure 9 summarizes the transmission options discussed in this section.

4. Public Policy & Externalities

The placement of long-distance HV transmission lines could involve certain externalities that should be taken into consideration when evaluating the overall impact such as on the environment and on biological life in the vicinity. These impacts are considered below and include the amount of land required by the ROW, health impacts, as well as radio interference. Comparisons are made between HVAC and HVDC overhead lines and not underground lines simply because of the relatively high cost of the latter in its implementation and maintenance as noted in the previous section (Figure 9). Further, as discussed below, the externalities associated with overhead lines are very minimal to begin with and, if quantified, would not present a cost of any significance over that of underground lines. Also, the fact that the transmission network would exist in rural areas away from population centers would also tend to minimize the impact of such externalities [29].

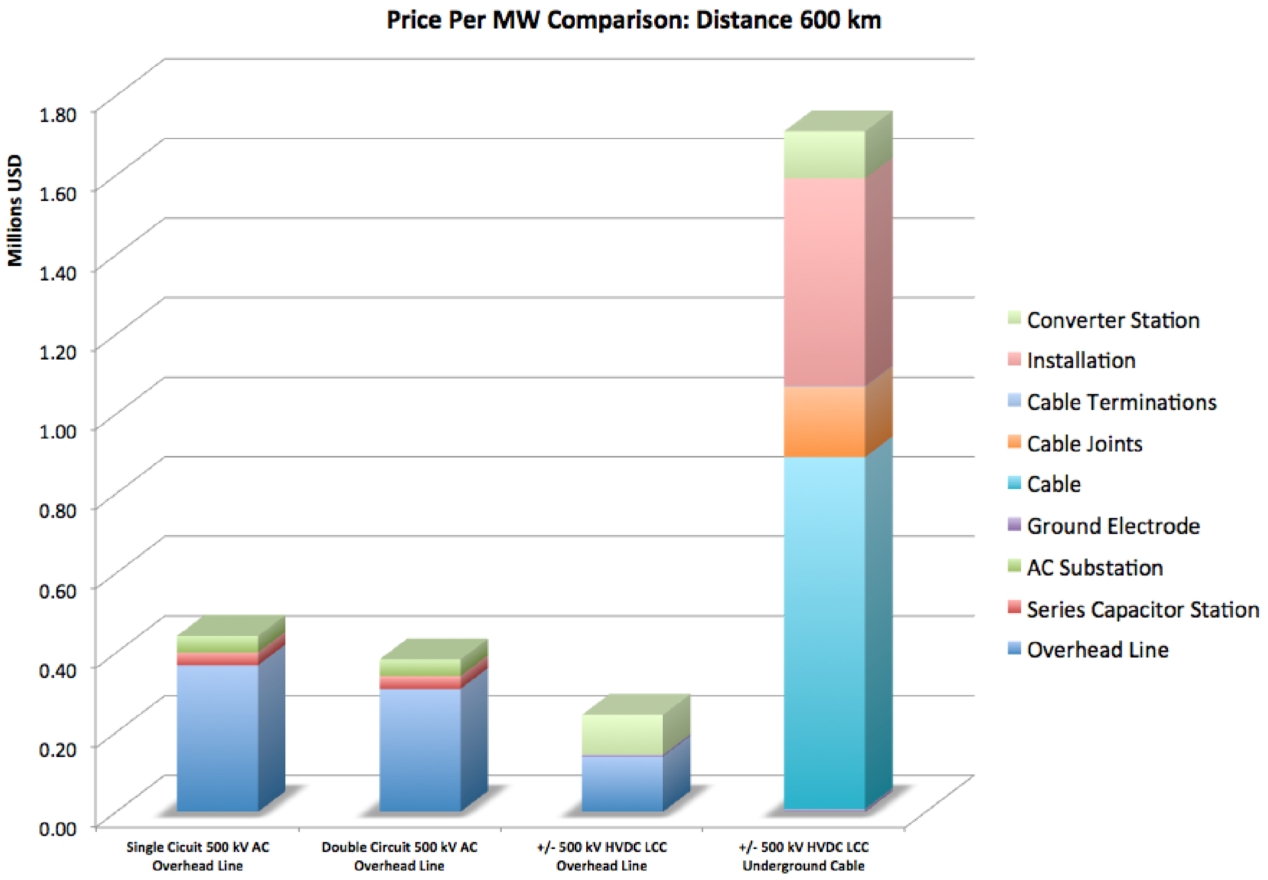

Figure 9. Price per MW cost comparison.

4.1.Land use

The amount of land required by the ROW for an HVDC transmission line is considerably less than that of HVAC. The latter requires 3 phases which, in general, would dictate the need for three separate lines supported by a row of 3 towers and thus a relatively wide ROW. HVDC, however, does not need more than 2 rows of towers and can be designed to include a single row of towers in the case of a monopole design. Figure 10 shows that the ROW for HVDC to be less than 2 times smaller than HVAC for a 6,000 MW network [30,31]. As a result, it is possible to install an HVDC line within the ROW of existing highways and railways. Even if it is possible to construct an HVAC network using a single-tower design, the ROW would be at least as much as required by HVDC. Thus, ROW as an externality cost for HVDC would be at least equal to or less than HVAC.

On the other hand, the converter station for an HVDC network requires a larger footprint than that of HVAC. A converter station for a 1,000 MW power line at a voltage rating of +/−400 kV would require a plot of land 320 m × 270 m, which is considerably larger than the substation as for an AC configuration [31].

4.2.Multi-state transmission lines

More often than not, the federal government plays a minor part in the siting of transmission lines. Approval at the state government level for transmission line siting generally occurs through public utility commissions and other agencies. Implementing wind energy becomes a challenge when power line siting crosses state borders. On an individual state basis, regulators are able to veto a multi-state transmission line. To do this, the state that is questioning the line can refuse to grant any necessary permits. States will do this when their state would not be receiving an acceptable amount of the benefits. This policy challenge is compounded by regulatory rules of federal, state, and local levels that authorize construction of transmission projects around the country [32].

Moreover, the Energy Policy Act of 2005 expanded the Federal Energy Regulatory Commission's (FERC) federal role in siting transmission lines. This was done for certain situations within the National Interest Electric Transmission Corridors (NIETC). Stakeholders often express concerns about FERC's upgraded authority to site transmission lines. One main concern that generally arises is how states and the public will be involved in the siting process. It is important to note that federal and state guidance encourages collocation of new transmission lines along existing transportation corridors [33].

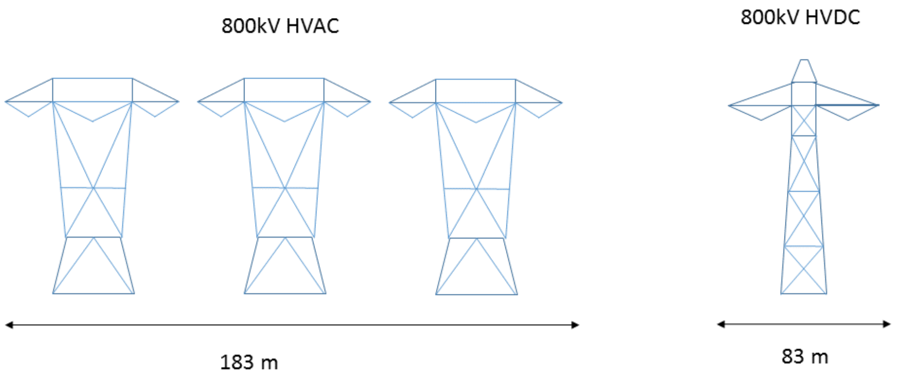

Figure 10. Right of Way Requirements.

4.3.Collocation risks

Potential safety and security risks come with the project of implementing new transmission infrastructure. From a safety standpoint, accidents from transportation infrastructure users (such as train derailments) could harm existing transmission lines.

Moreover, fallen transmission lines could potentially damage transportation infrastructure. Another safety issue is the potential for maintenance workers to be injured. This is due to an increased safety risk from the close proximity of transmission lines to transportation ROWs. From a security standpoint, collocation may make the corridor a more attractive target [target of?]. Several approaches to mitigate potential risks of collocation have been studied and proposed on an array of projects in the United States.

Collocation risks generally occur along pipelines, railroads, and highways. Mitigating the pipeline issue starts with making sure that electric current emitted from the line will not interfere with cathodic protection. This is required under the Pipeline and Hazardous Materials Safety Administration regulations. Mitigating the railroad issue starts with ensuring that the transmission line magnetic fields won't interfere with railroad signal systems. Lastly, the mitigation of the highway issue starts with encouraging assessments of potential collocation risks. Owners and operators should ensure that transmission towers and lines won't interrupt traffic operations [33].

4.4.Health Risks

The effect of an electric current flowing along a transmission line is the induction of an electromagnetic field in the surrounding region. For a given conductor, higher voltages result in stronger magnetic and electric fields. As HVDC is emerging as a viable and efficient means of transferring electric power over long distances, there has risen a concern over the effects of the resulting electromagnetic fields on the environment, including the impact on human and animal life. Herein brings forth the results of several studies, which have attempted to answer concerns regarding HVDC-related health risks.

One such study was initiated per an expressed public concern over an underground HVDC line that was laid for power transmission between England and Ireland [34]. The resulting report states that the magnetic field 1 meter from a HVDC line is not stronger than the Earth's magnetic field, which is of order 50 microtesla. Physiological responses have been observed in medical test cases in the presence of a magnetic field, but only for a field nearly 1×10^5 times this strength. At 8 tesla humans can suffer a sense of vertigo and nausea. Medical tests have shown that a field greater than 15 tesla can reduce the blood flow in the aorta by 10%. Fields of such strength are far beyond what is experienced near an HVDC line and the report concludes that there exists no human health risk.

This benign conclusion concurs with the independent assessment of the International Commission on Non-ionizing Radiation Protection (ICNIRP), which has studied the potential hazards of magnetic and electric fields associated with HVDC transmission lines. The ICNIRP consists of a panel of scientists and physicians from various countries. Their recommendations are recognized by the World Health Organization (WHO). In 1994 and later in 2009, the ICNIRP in its reports has asserted there is little evidence to suggest physiological impacts in a magnetic field below 5 tesla [35,36]. Being cautious, however, they offered guidelines to suggest short-term exposure to strong magnetic field should be less than 2 tesla for occupational workers and 400 millitesla for the general public. Individuals with pacemakers, however, should avoid exposure above 0.5 millitesla. These limits are yet far above the magnetic field as encountered in the vicinity of an HVDC line.

Besides possible direct impact of the magnetic field, another study considered the possible hazard presented by the electric field or by charged air ions that are themselves a product of an electric field [31]. Although the human nervous system as well as pulmonary system could potentially be impacted by an electric field, there is no conclusive evidence that exposure to an electric field associated with a 450 kV line, either short- or long-term, is of significance. The effect of charged ions on the respiratory system resulting from an electric field of such strength is also negligible as the number of ions produced is no more than naturally occurring in the vicinity of a waterfall or at the seashore. However, for HVDC lines carrying a voltage of order 1000 kV, a health consideration may be of issue especially during precipitation events, during which positive ion concentration can exceed 105−106 cm^3. Relatively long exposure to ion concentrations above 10^4 cm^3 can affect the respiratory tract [37].

Various effects of the electric field as have been observed by humans in the vicinity of HVAC lines are either greatly minimized for HVDC lines or not observed at all, such as the electric discharge. The ion current flowing through a human under an HVAC line of order +/−1000 kV is 200 μA, while a HVDC line of comparable power transmission induces an ion current only about 1/100 this amount [37]. Further, the build up electric charge of large vehicles with rubber tires parked under high power lines, which for HVAC can be significant and even dangerous, is not a concern with HVDC.

4.5.Radio interference

Another area of possible environmental impact by HVDC transmission lines is electromagnetic interference within the radio frequencies. Such interference is related to the corona, which is an electric discharge due to ionization of the air around a conductor. Such corona effect exists for HVAC lines as well as HVDC and in fact is generally of higher amplitude for HVAC [38]. Corona discharge and associated radio interference increases exponentially at a greater rate with HVAC as compared to HVDC. That is, radio interference is proportional to En, where E is voltage gradient. Tests have shown that the power exponent n is generally 5−7 for HVDC lines and 7−8 for HVAC lines and thus given lines of comparable voltage, interference by HVDC is considerably less [39].

5. Application in Iowa

The purpose of the discussion thus far has been to identify the various technological, environmental, and economic factors associated with HVDC transmission. To gain an understanding of the relevance or importance of these factors, it is worthwhile to discuss them relative to the implementation of an HVDC network over a specific region. We chose Iowa as a focus area because it is the largest producer of wind energy per unit area in the US and also because of the great potential for further expansion in the number of wind farms in Iowa. To-date, however, significant growth has been hampered by the lack of means for transporting the electric power to out-of-state markets.

It should certainly be mentioned that efforts are currently underway through the Rock Island Clean Line Project to construct an HVDC line to transport power from northwest Iowa, where the highest concentration of wind farms exist in the state, to large population areas such as Chicago and other cities to the east [40] (Figure 11). Current plans are such that the Clean Line Project will enable the transmission of 3,500 MW of electricity, which is enough to power 1.4 million homes. Beyond a significant expansion in the capacity of the regional power grid and providing power to large population centers outside of Iowa, it is touted that the project will benefit Iowa as well by bolstering the local wind energy industry, which will translate into increased jobs and increased tax base for local governments [40]. Impact studies were conducted by different consulting firms [41,42], which identified economic and environmental benefits of such a transmission project shown in Figures 11–12.

Having thus established the significant positive impact an HVDC transmission line could bring to Iowa, for example as proposed by the Clean Line Project, it is prudent at the same time to consider cost as well as any potential environmental impacts. The intent of this paper, in particular, has served to compare system designs based on either HVDC or HVAC and to ascertain the optimal technological solution in consideration of cost and externalities such as environmental concerns.

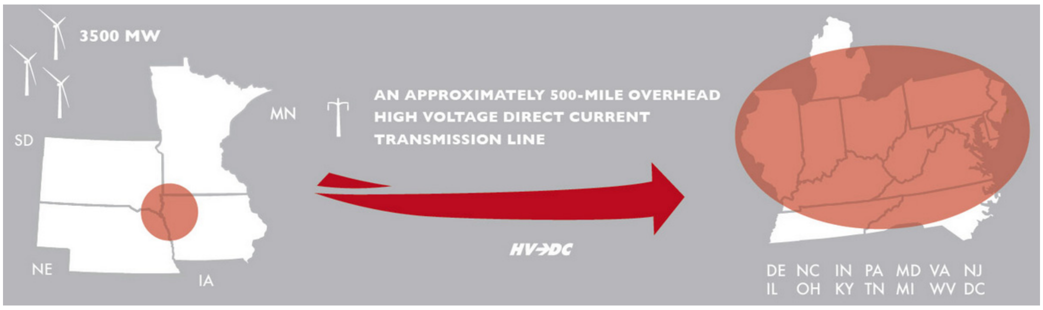

Figure 11. Rock Island Clean Line Project [40] (Used by permission from Clean Line Energy).

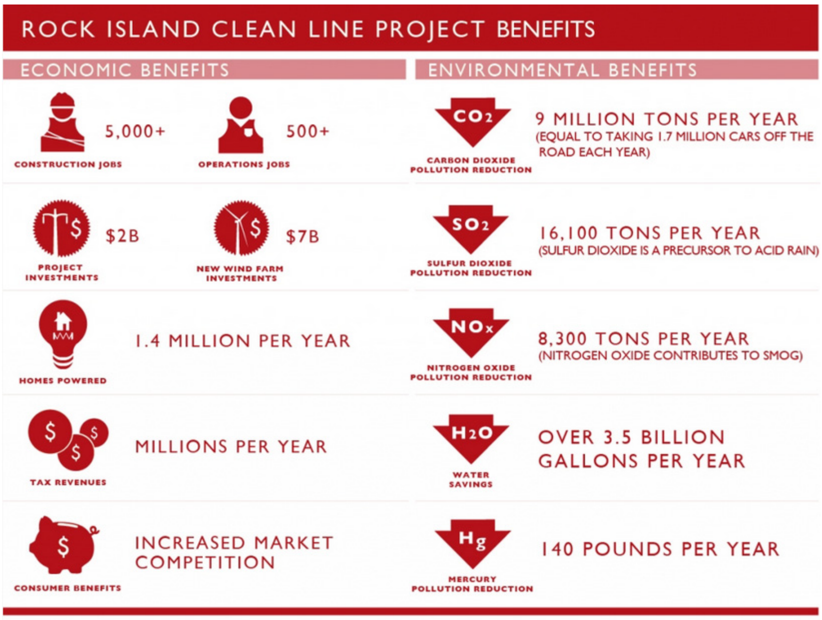

Figure 12. Rock Island Clean Line Project Benefits [40] (Used by permission from Clean Line Energy).

Considering several options that involved HV lines with either DC or AC, it was found that overhead HVDC lines were economically the most feasible for transmission lines extending greater than 600 km. Indeed, this approach concurs with that of the Clean Line Project, which plans to transport energy from NW IA to central IL, a distance of greater than 800 km.

According to the economic analysis in Section 3, it could be assessed that an HVDC line of 800 km length would be approximately 30% less expensive to build and maintain than an HVAC line. This economic assessment was in consideration of: cost of transmission lines and towers, converter station installation, and system power loss. The cost of land for the ROW of the lines was not considered, but is significantly less for HVDC and would further reduce the overall system costs.

Environmental factors related to HVDC transmission lines are in Iowa, as in any locality, negligible. Health risks are minimal and even at times less than those of HVAC lines. The ROW for overhead HVDC lines is less than HVAC and could be installed using the ROW of existing inter-state networks such as highways, railroads, and current HVAC paths, a solution that would help minimize the "not in my backyard" concerns of adjacent land owners, which is an issue that has arisen recently in Iowa in response to the Rock Island Clean Line project [44].

In the above discussion, it should be clarified that the design assumes a point-to-point long-distance connection (i.e., a radial design) as opposed to a mesh design. Such a design concurs with the overall purpose of exporting wind power to locations outside of Iowa, the economic benefits of which have already been discussed. Designing a system that would allow for direction of power for use in-state would involve transmission lines of shorter distances (e.g. below the 600 km "break-even" distance) as well as the installation of more HVDC converter stations, both of which would significantly increase the cost of the network.

6. Conclusion

Based on what is discussed in the subsequent sections, HVDC represents the solution over HVAC for transporting electric power over long distance to markets outside of Iowa. As discussed above, HVDC is most beneficial for long-distance transmission and thus fits the scenario for Iowa as a major exporter of electricity for wind power. Implementing HVDC, however, for power supply within Iowa would not provide much economic benefit because the footprint and installation cost of a converter station is much larger for HVDC and cost per length-of-line is higher as compared to HVAC when considering transmission distances less than approximately 600 km. The incorporation of HVDC technology thus would not result in an increased power supply for local communities, but yet would have a significant and positive economic impact through the export of power out-of-state and thus means for encouraging continued growth in the wind power industry along with job creation and tax revenue.

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Conflict of Interest

All authors declare no conflicts of interest in this paper.

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