Cost Analysis and Profitability of the Cable Train: A Mobile Platform for Manufacturing Underground Cable Systems

by

Richard C. Bratten

Submitted to the
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in Partial Fulfillment of the Requirements for the Degree of

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ABSTRACT

As the profitability and technological viability of renewable energy projects continues to improve, the issue of connecting remote supply and demand becomes increasingly important. In certain instances where supply and demand locations are far apart, high voltage direct current (HVDC) power transmission lines become more efficient and cost effective than traditional alternating current lines. Installing overhead HVDC cables is sometimes the simplest, cheapest solution to this problem, but there is often difficulty in getting these projects approved due to public displeasure as well as higher security risks. The alternative solution, laying underground lines, can be four to fourteen times more costly than overhead lines [1]. However, over long distances, there is a break-even distance where underground HVDC becomes more efficient than overhead because of factors such as lower power losses, less accessories are necessary, and a smaller right-of-way is required [2]. Luke A. Gray, Professor Alexander H. Slocum, et al. have proposed a method of transporting raw materials along existing railroad lines and continuously manufacturing and laying HVDC cables in trenches made along the railroad's right-of-way. We hypothesize that it is possible to lay HVDC cable at a lower cost than traditional methods by using this newly proposed solution. This paper investigates the cost breakdowns of both the overhead and operating costs involved in a "Cable Train" HVDC cable manufacturing system and does a fiscal analysis of profitability and potential for scaling. The overhead costs of the "Cable Train" provide a relatively high barrier to entry at $61 million, and operating costs for the project in our chosen configuration are $2.8 million per mile. Compared to $21.1 million for other projects discussed in this paper in the same configuration, the Cable Train lays cable at a much lower cost. For expected project lengths of over 100 miles, overhead becomes relatively small, indicating high potential for the "Cable Train" to be used on different projects. Methods used to calculate the costs of overhead on the "Cable Train" rely on quotes (minimum of two) provided by anonymous vendors, while operating costs largely rely on industrial estimation methods requiring two or more statistics gathered by myself, Gray, or by data conglomerates.

Thesis Supervisor: Professor Alexander H. Slocum
Title : Walter M. May and A. Hazel May Professor

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I would like to thank Professor Alexander H. Slocum and Luke A. Gray for their endless support and patience in helping me write my thesis. Alex always has very limited time due to the number of amazing projects he has to run, but he is always quick to email back to my questions and has been an invaluable resource for this project. When Luke and I go chasing data down a rabbit-hole, he never fails to pull us out and set us back on track. Similarly, this project would not be possible without Luke's endless dedication and passion. Since long before I started working on this project, Luke has been tirelessly mucking through details of the Cable Train, calling companies, and asking the right questions to get this project off the ground.

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1. Background and Concept Introduction of the Cable Train

In recent years, decarbonizing both industry and energy consumption has been at the forefront of many institutions' policies at the corporate and national levels. With the advent of improved renewable energy resources, there is also an increased desire for renewable grids. In order to meet current and expected demand for these renewable grids, long-distance transmission linkages must be created to connect sources of renewable energies to their respective grids. Underground HVDC direct linkages are the most appropriate choice for these long-distance scenarios for a couple of reasons. Current energy transmission systems consist of overhead cables that are subject to weather, geo-magnetically induced currents, and pose a relatively high security risk when compared to underground cables. In addition, HVDC systems are more cost-efficient over long distances than HVAC systems due to lower transmission losses and amortized fixed costs. Finally, underground HVDC direct linkages are a particularly good solution for renewable energy resources because much of the wind and solar energy being generated today (particularly in the U.S. and China) is landlocked, meaning that undersea cables cannot transmit this energy to demand locations.

Currently, there is no solution to this power transmission disparity problem. How can we connect large renewable energy-generating resources to high-demand locations on a grid? Undersea cables can be laid in a continuous manner, but it would be impossible to take their schematics and apply it to a land-based vehicle of the same size. Furthermore, cable manufacturing requires precision, logistics require time and space, and construction is difficult and costly. Our proposed solution is the "Cable Train", which, using existing railroad tracks and right-of-way would lay HVDC cable in-situ continuously. Rolling stock would carry raw materials, convert them into the necessary components, and lay them in the existing right-of-way (see figure 1). The rail system is ideal for this application as it is meant to be well-maintained and carry heavy machinery. Furthermore, additional rail cars can be made to prepare a trench for the cable, line it with concrete, and cover it afterwards (see figure 2).

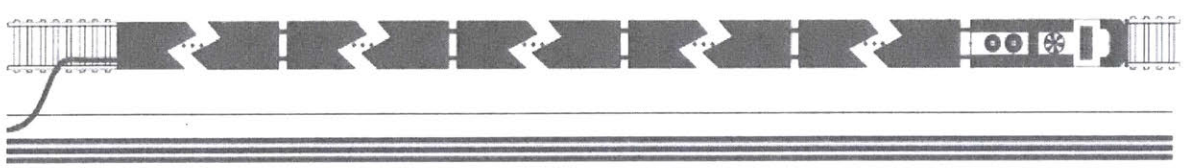

Figure 1: A top-down representation of the Cable Train laying high voltage cable into concrete-lined trench. The train contains the heavy machinery to complete wire stranding, extrusion, curing, and degassing, as well as for trenching, concrete slip forming, and other necessary operations.

The Technological Proof-of-Concept and the Economic Analysis Tied Together

The concept of the Cable Train, as devised by Luke A. Gray, Professor Alexander H. Slocum et al. is a technologically feasible creation that has been undergoing rigorous industry review since its inception. Proof-of-concept devices and work done by Gray are very thoroughly discussed in his own paper, "Cable Train: A Mobile Platform for Manufacturing and Installing UGC Transmission Systems", and serve as a backbone to this thesis, but the idea is incomplete without one or the other. Thus, these two works are closely intertwined and serve to support one another to form a comprehensive conceptualization of the Cable Train. The vision for the capabilities of the Cable Train is vast and broadly applicable to the power transmission and communications industry, and along with the technical possibilities of the Cable Train, the economic potential scales as well with larger projects. Ultimately, the Cable Train should be seen as an industry-driving innovation that will change the HVDC market, paving the way for renewable energies while also being a profitable investment.

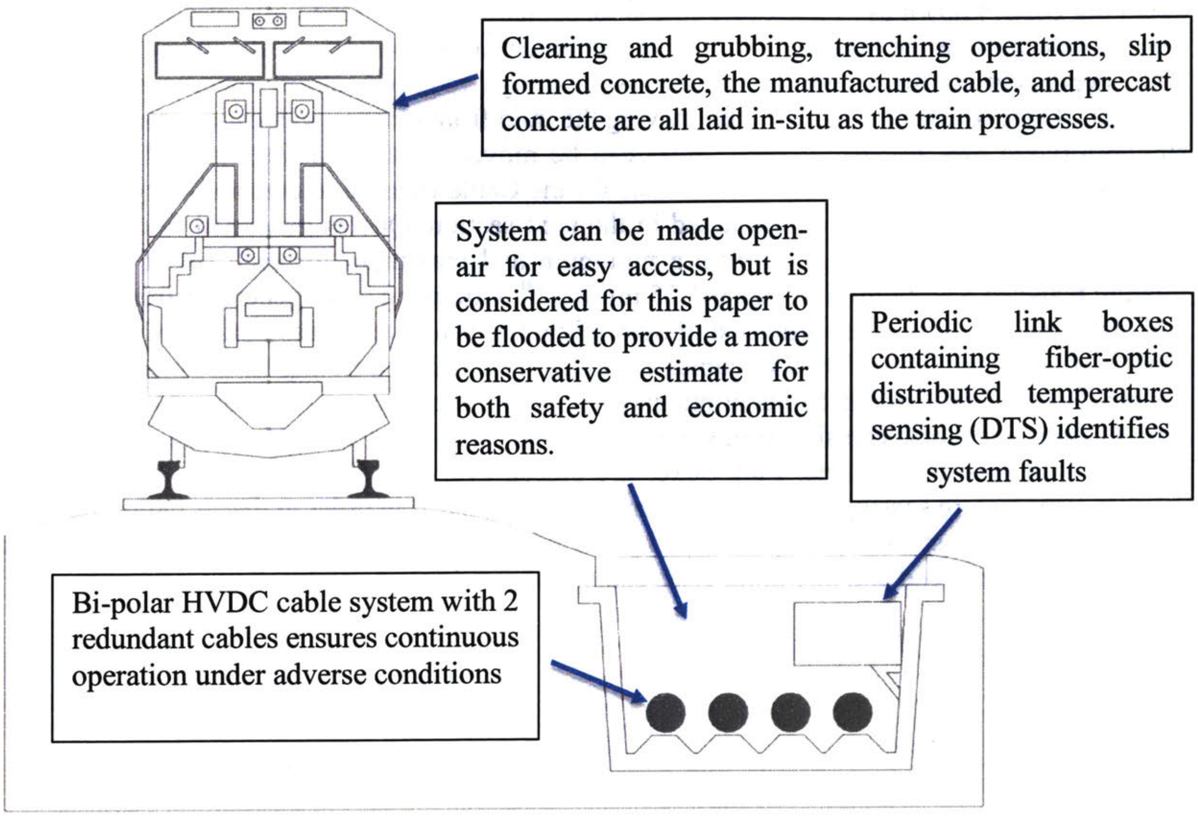

Figure 2: A front-facing representation of the "Cable Train," as well as the slip formed, concrete-lined trench that HVDC cable will be laid into and subsequently covered with precast concrete. Link boxes placed approximately every 1.5 miles [5] with DTS equipment will be able to detect inconsistencies and faults, leading to quick restoration of equipment, while redundant cables ensure that the transmission line will not go down completely.

2. Economic Modeling of Overhead and Operating Costs

Economic modeling of the Cable Train has been broken down into two costs for the purposes of this research: overhead and operating. Additional costs exist, including transmission loss costs, operating and maintenance costs, and environmental considerations. These costs are not insignificant, but are incurred over the lifetime of the project and can only be estimated based on a very detailed project scenario where power capacity, cable voltage, vegetation density, and a variety of other factors are known. Instead, economic modeling based on overhead and initial operating costs, known as "First Costs" [3], is discussed. The overhead costs of creating a Cable Train would present the highest barrier to development of the project, while operating costs are more dependent on the length and transmission design requirements of specific projects and contracts. Once overhead costs are met, moving the train from location to location is a much more straightforward task because a single train can be moved on the existing railroad network to multiple projects. The bulk of overhead costs for the Cable train lie in custom heavy machinery specialized for this application, discussed in the next section. Quotes generated from calls with anonymous companies was given with a minimum and maximum for each set of equipment, totaling between \$52.25 million and \$61.15 million [4]. Operating costs generated from estimates and historical data give a per-mile cost of \$2.8 million, given several assumptions. Our system is dipole, so there are two 1500MW cables operating at 550kV operating in conjunction as one system. Because the cable is laid continuously and is DC, there are no joints or cable accessories such as surge arrestors. The slip formed concrete trench is flooded after the cables are put in and covered with pre-cast concrete. Link boxes are placed every 20-50km [5] (32-80 miles) so that discrete temperature sensing (DTS) equipment [6] can be placed in order to detect faults. The bulk of the operating cost (86%), is produced by the manufacturing of the cable. A more detailed breakdown of overhead and operating costs can be seen in Table 1.

Overhead and Operating Costs of the Cable Train

Capital Components Grouped by Function	Approximate Cost (USD)
Wire Payoff, Planetary Strander, Closing Die/Bench, Taper, Caterpillar/Capstan, Dancer, (Installation)	$2,000,000 to $2,500,000 (+$600,000)
MDCV Line w/ Triple-Extrusion and LLD Curing (Installation)	$15,000,000 to $17,000,000 (+$5,000,000)
Degassing w/ 80 Cars, 4 Drums per Car, Capable of 28 Day Degas at 80 m/hr Production Rate (Installation)	$10,000,000 to $12,000,000 (+$3,000,000)
Armouring Payoff, Armouring Machine, Caterpillar/Capstan, Dancer, (Installation)	$500,000 to $700,000 (+$150,000)
MDCV Line w/ Single-Extrusion and LLD Curing (Installation)	$6,000,000 to $8,000,000 (+$3,000,000)
Caterpillar, Dancer, Buffer, (Installation)	$300,000 to $400,000 (+$100,000)
QA: Tensile Testing, Weathering, Boiling Pool, Convection Oven, Generators, Transformer, (Installation)	$500,000 to $600,000 (+$100,000)
Primary Mover 6,000hp ×2	$6,000,000 to $8,000,000
Total Cost for Major Machinery, Rolling Stock, and Installation	$52,250,000 to $61,150,000

Operating Components Grouped by Function	Approximate Cost (USD) per Mile
Civil Engineering, Earthwork, Trenching Operations	$29,000
Slip Formed Concrete, Precast Concrete	$225,000
Cable Manufacturing (2 Cables, Totaling 3000MW), (Installation)	$2,411,000 (+$60,000)
Commissioning, Pumps, Link Boxes, Small Components	$55,000
Fuel Costs, based on power used	$13,000
Total Cost for Major Operating Components (Per Mile)	$2,793,000

Overhead and operating costs can be associated by a scenario:

- Bipolar, 550kV cable rated to 3000MW
- A trench for the cable has been dug and lined with slip formed concrete, covered with precast slabs
- Link boxes every 20-50km [5] house equipment to detect faults
- For a 100-mile project across normal terrain situations

Total Project Cost: $340,450,000

Table 1: A more detailed breakdown of overhead and operating costs presented with some uncertainties based on supplier quotes and safety factors. All operating costs apart from cable manufacturing cost include a safety factor for "O & P", contractor markup and profit, as recommended by RSMeans [12]. For HVDC projects, long distances (>100 miles) will amortize overhead costs as cable manufacturing costs per mile begin to dwarf heavy machinery costs.

3. Cable Train Overhead Technology Costs

There are a number of important technologies to be considered when funding the initial installment of the Cable Train. Due to the fact that this project exists as a new way of using existing technology, many of the technological innovations of the train come from method rather than physical inventions. In this section, we will discuss the functions and costs of the equipment being mounted to the Cable Train. Gray estimates that the total cost of all the technological equipment of the Cable Train will be about $61 million [4] using conservative, upper-end estimates. A coarse schematic of the components of each Cable Train component is shown in Figure 3.

- **Primary Mover(s):** The primary movers of the Cable Train house the engine and drive the Train. The movers are not unique to the Cable Train, and can be bought from companies in the same way that they are for traditional cargo or passenger trains. Estimates range from $6 to $8 million [4].
- **Extrusion and Curing:** The horizontal triple extrusion method described in Luke A. Gray's "Cable Train: A Mobile Platform for Manufacturing and Installing UGC Transmission Systems" [4] is a method for the manufacture of HVDC cable that accounts for the largest overhead cost of the project. Due to the new technological developments and heavy machinery required to draw wire into the lengths and areas required by HVDC cable, the cost of this feature alone could be as much as $17 million. As one of the most crucial pieces of the Cable Train, this vital piece requires both precision and accuracy and thus has a high price associated with this quality.
- **Conductor Stranding:** Conductor stranding is one of the first processes to occur in cable manufacturing, and deals with weaving extruded wires together in a particular pattern to increase flexibility and durability that is much greater than its un-stranded counterparts. While not as expensive as the extrusion process, stranding also requires heavy precision machinery and will account for a significant portion of the project.
- **Inline Degassing:** Inline degassing of the conductor is another technologically challenging aspect of this project. Degassing is an important process for HVDC cable as it improves the quality of the cables, the reliability of electrical testing on them, and their dielectric properties [7]. Degassing costs will similarly not be as high as the initial extrusions, but will be sizable for the Cable Train, on the order of $10 to $12 million [4].
- **Conductor Shielding:** An extruded thermosetting plastic is necessary to separate the conductor and the layer of insulation following. A conductor shield protects the insulation layer from heat and must conform to ASTM standards. Associated costs of conductor shielding will not be as high as the prior processes.
- **Insulation:** The insulation layer is significantly thicker than the conductor shielding and will cost more accordingly. The insulation layer, thick for HVDC and even thicker for UHVDC, is a considerable ratio of the overall diameter of the cable because of its protective capabilities.

- **Metallic Shielding:** In traditional cables, metallic shielding of extruded cables is necessary to protect it from electromagnetic activity and from capacitative buildup, but in HVDC cables it also serves to protect its own jacketing from damage. At extremely high voltages, discharges can pierce insulation and even jacketing, so to prevent this, metallic shielding is necessary to absorb such discharges. The cost of the metallic shielding layer will not be considerably more than its material cost and will be relatively small compared to extrusions, degassing, and other early processes.
- **Jacketing Extrusion:** The creation of the cable's outer jacket is another extrusion process that is considerably less than the copper extrusion process, but still sizable. For HVDC cable, jacketing must be thick and uniform, strong and reliable enough to protect the cable from all kinds of interference.
- **Production Testing:** Production testing is a large unknown in the operating process of the Cable Train. Due to the lack of existing regulation and standards in the HVDC industry, Chinese power transmission companies have been leading the way and setting precedent for responsibility and testing procedures. On the Cable Train, several carts may be dedicated to in-line or post-production quality control, quality assurance, and testing operations, but the extent of these operations has not been decided upon as of yet. As regulators catch up to the industry, this process will become more defined and a more methodic approach can be taken to this issue.

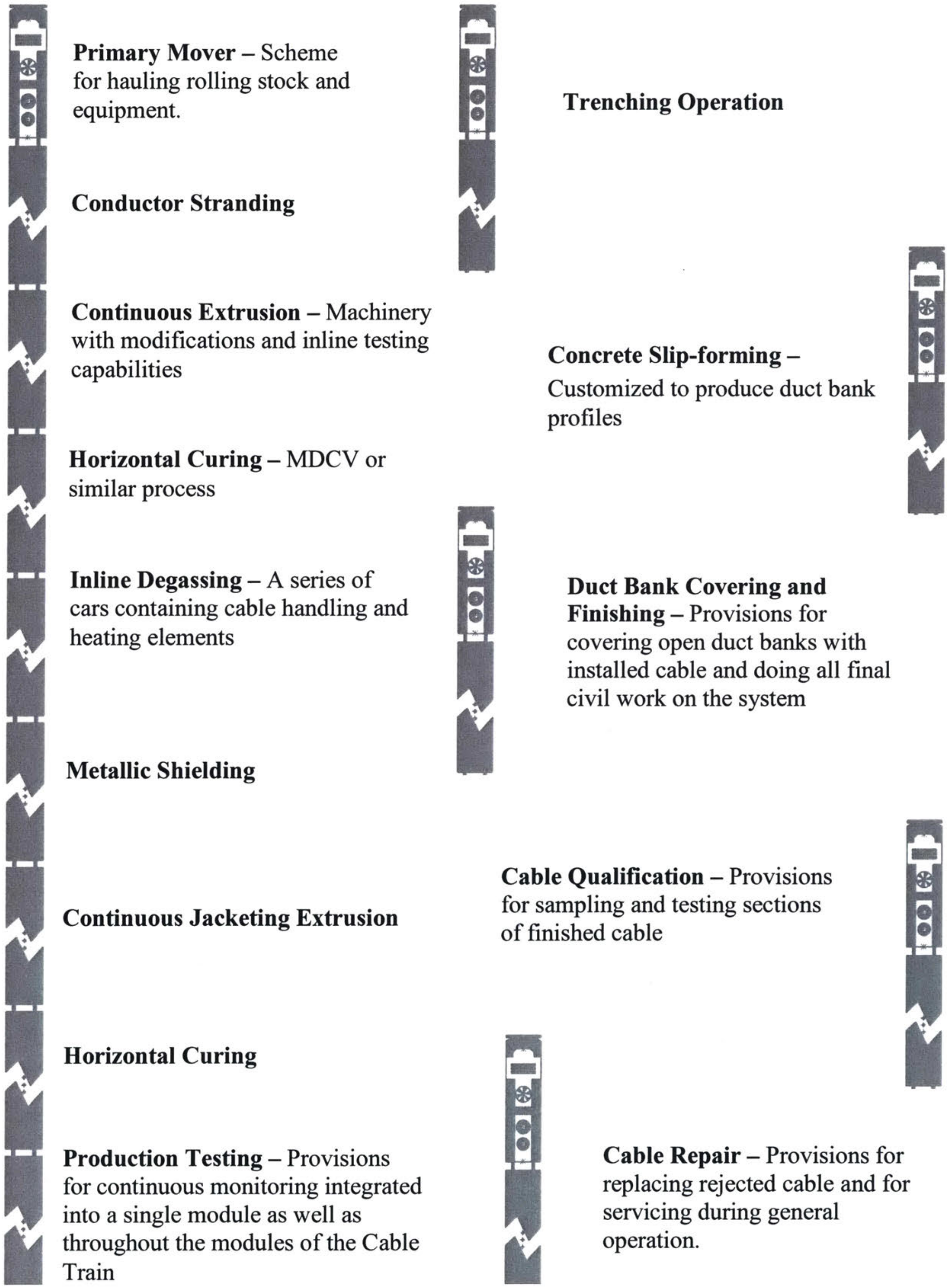

Figure 3: A top-down schematic of the Cable Train and its subcomponents, laid out in order of operation. Prior to the Cable Train, survey work will be done, as well as necessary steps for the preparation of clearing and grubbing.

4. Operating Costs of the Cable Train

Operating costs are the costs incurred during the Cable Train's ongoing use. In the case of the Cable Train, the operating costs scale with the length of the line being laid and deal with the costs associated with laying additional cable. In addition to the Cable Train, the main focus of this project, additional trains could contribute to operating costs and may need to be run beforehand to clear and grub the land for use and to lay down the initial slip form to put the cable in rather than be on the Cable Train itself. The operating costs for the Cable Train itself are the most significant for the project regardless and have the greatest impact on the bid price, and therefore total profit. The largest operating cost of the project is by far the manufacturing of the cables, contributing 86% of the total cost of the project for only one cable. For larger projects, using an example where a bi-pole system with 2 redundant cables is used, this percentage jumps up even higher to 92%. The cast-in-place concrete lining the trench to protect the cable (4.9%), the precast concrete cover (3.2%), and installation costs (2.1%) for the project account for most of the remaining cost. Figure 4 shows a snapshot of the operating costs of the Cable Train as well as a representation of how it breaks up proportionally.

Work Tasks	Per Mile Cost	
Surveying	$	4,291
Clearing	$	8,727
Rubbish/debris Removal	$	127
Trenching	$	15,981
Slipform	$	136,756
Cable Cost	$	2,410,974
Cable Installation	$	59,806
Precast Cover	$	87,995
Pumps	$	804
Commisioning	$	27,255
Rehabilitation/Cleaning	$	27,255
Fuel Consumption	$	13,049
TOTAL	$	2,793,019

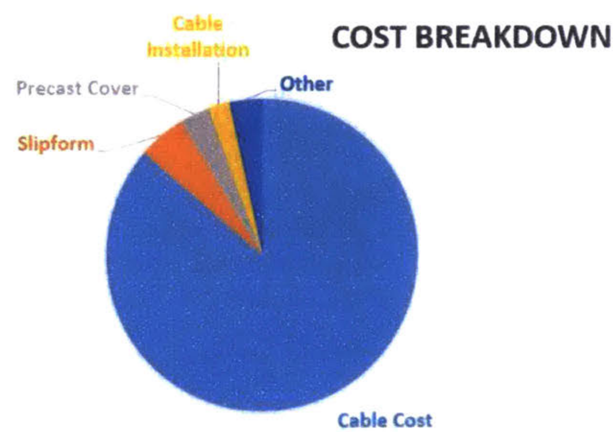

Table 2, Figure 4: A detailed breakdown of the operating costs of the Cable Train. The cost of cable manufacturing is overwhelmingly the largest percentage of total cost (86%), and increases for each additional cable required. The next largest costs are that of concrete (a combined 8.1%), and the cable installation cost (2.1%).

4.1 Cable Manufacturing Cost

Figure 5: Cross-Section of a XLPE HVDC Cable [4]

A typical manufacturing process for HVDC cable consists of applying several concentric layers around a conducting wire. Copper or aluminum wire is extruded and wound in a specific orientation, wrapped in a conductor shield, multiple insulation layers, a metallic shielding component, and finally a jacket. As voltage increases, certain components must be thicker to allow for the larger voltage. The conductor shield must be significantly thicker to protect against discharge, and the jacket also must be thicker for similar reasons. Because the Cable Train has to continuously manufacture each of these separate components, and because each of the materials has to be acquired separately and then integrated into the process, this is the most expensive operating cost. By taking cable manufacturing cost estimates from separate sources [2,8,9,10], converting to 2018 USD amounts [11], and normalizing the cables by 3000MW, we find that the average manufacturing cost of an HVDC cable system of this capacity is $2.4 million per mile. 3000MW is the size of a typical, relatively small power transmission project and is a decent approximation for local work. For the purposes of the Cable Train, while we believe this application is a good approximation of the projects that would be undertaken, it has the potential to scale up to larger projects as well. The Three Gorges Dam, for example, generates 22,500MW [4], and would require 8 times as many cables to transport its energy across China. While this is an absolute project maximum in the world today, the applications of the cable train certainly could extend up to this order of magnitude. However, for an average project estimate of two cables being used in a dipole system (a total of 3000MW), the cost associated with cable manufacturing is estimated at $2.4 million per mile for the purposes of the Cable Train.

IEEE		
Cost per Mile in Original Units	$	1,950,000.00
Date of Original Paper		2007
Exchange Rate		1.00
Rate of Inflation		1.18
Convert to 2018 USD	$	2,303,437.50
Normalized by 3000W	$	2,303,437.50
U. Applied Sciences		
Cost per Mile in Original Units	$	434,959.70
Date of Original Paper		Nov 2011
Exchange Rate		0.74
Rate of Inflation		1.09
Convert to 2018 USD	$	348,870.87
Normalized by 3000W	$	1,395,483.48
Imperial College, UK		
Cost per Mile in Original Units	$	730,110.93
Date of Original Paper		2016
Exchange Rate		1.41
Rate of Inflation		1.00
Convert to 2018 USD	$	1,029,456.40
Normalized by 3000W	$	4,276,927.31
IEEE		
Cost per Mile in Original Units	$	1,613,200.00
Date of Original Paper		2014
Exchange Rate		1.00
Rate of Inflation		1.03
Convert to 2018 USD	$	1,668,048.80
Normalized by 3000W	$	1,668,048.80
Normalized Average	**$**	**2,410,974.27**

Table 3: The cost of HVDC cables, averaged and normalized by 3000MW. Details taken into consideration included the inflation rate of currency, exchange rate from the original country, and the normalization of power capacity to generate an accurate comparison and average.

4.2 Surveying

Surveying, the process of appraising and accurately mapping the land of a project before starting work, is a very important step so that accurate readings can inform the engineers of how to work on the project. Since land is constantly changing and reforming, survey work needs to be done even if reports already exist for the project site. Such reports are likely to be outdated and will not accurately apply to how the land exists in the field. Surveying is a relatively easy cost to estimate as guidelines for civil engineers exist for nearly every conceivable situation. By using a conservative estimate of the maximum per acre cost associated with surveying difficult terrain [12], and by considering an 8-meter right-of-way in which to operate, the cost of surveying per mile is estimated to be $4,291. On the scale of the project, this is a relatively minor cost, consisting of 0.15% of the total project cost.

Dollars per Acre		4425
ROW Width (Feet)		8
Feet per Mile		5280
Square feet per acre		43560
Total Cost Per Mile	$	4,291

Table 4: The underlying geometric calculations behind civil engineering surveying costs. Surveying is assumed to be conventional topographical surveying, including materials, labor, and equipment as outlined by RSMeans [12].

Note: [12] RSMeans Data from Gordion is a cost estimation data compilation used by professional engineers and estimators. It is a large conglomeration of various construction data points across hundreds of projects, and should be taken in this paper as multiple sources of data. **Data taken from RSMeans also includes a safety factor for "O & P"**, which is the overhead and profit markup charged by contractors.

4.3 Clearing and Grubbing

Before trenching can occur, a sufficient space must be cleared and grubbed of brush and undergrowth. Standard contractor estimates for the labor and equipment involved in clearing and grubbing can vary based on density of the underbrush and the size of trees being removed. By using the more expensive, conservative estimate ($9000 per acre) for thicker underbrush with trees of a 12" diameter [12], as is characteristic of the Midwest and East coast, and a ROW of 8 feet as described in section 2.2, the per mile cost of clearing and grubbing is estimated at $8,727. In addition to typical contractor estimates for the labor and equipment involved in the clearing and grubbing process, the cost of disposal must also be taken into account. Estimation methods drawn from RSMeans estimation data compilation put the average costs of the disposal services much lower than that of the clearing and grubbing process, on the order of 100, but it should not be neglected. The cost of debris removal containers of 10-ton capacity (the highest available using our estimation methods), will require additional train cars, adding to overhead costs at a rate of ~8.4 tons of debris per acre [13], or 0.013 tons per square mile. Because the ROW of the project is only 8 feet, a project of 100 miles will produce a tonnage of 11.54 tons, requiring only 2 containers and therefore costing a mere $254 to remove.

Dollars per Acre		9000
ROW Width (Feet)		8
Feet per Mile		5280
Square feet per acre		43560
Total Cost Per Mile	$	8,727

Table 5: The underlying geometric calculations behind clearing and grubbing. Clearing and grubbing consists of removal of all foliage, including stumps of up to 12" diameter and includes both labor and equipment.

An alternative would be to have a continuously operating rail mounted system with an extended reach arm that carries quick change tools such as a harvester/buncher, forestry shredder, brush cutter, and flail mower for example, or one arm for each. The goal would be to clear and shred organic matter in a continuous manner and either place harvestable logs on a flatcar and leave the shredded material as mulch, or vacuum up the mulch as it is created and deposit it into a container on rail car where the container is easily changed out when full. Figures 5 and 6 demonstrate the validity of this operation, and the heads can be changed on each boom. Similar estimates would be on the same scale as the disposal services, on the order of $200-$999.

Figure 6: Rail-Mounted Brush Cutter [14]

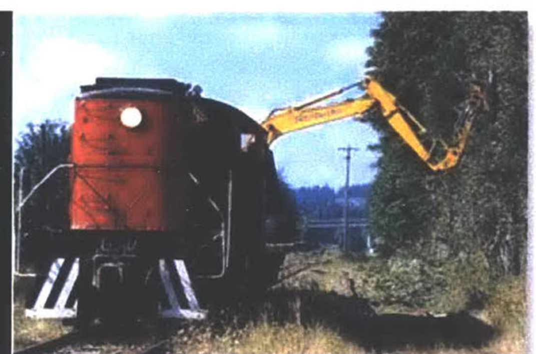

Figure 7: Rail-Mounted Third-Boom Brush Cutter [15]

4.4 Trenching

After land is cleared and grubbed within the right-of-way of the Cable Train, trenching can occur. Trenching is a method of excavation particularly useful for cable-laying because it can be done in one pass over very long distances. While trenching could be done by mounting another machine onto the cable train and continuously operating, existing trenching machines could also continually make the trench and place the excavated material next to the trench. To cast a concrete trench liner with the required dimensions of the culvert described in the next section, with outer diameter 3.2 meters, a trench of 4.02 m^2 cross-sectional area must be excavated. Trenching operations in volumetric units are well-documented by RSMeans, which takes in data from thousands of projects across the world, and conservative estimates of excavation for common earth [12] using larger machinery puts the cost of this operation at $15,981 per mile. Of course, different types of soil will change the pricing of the excavation as well. Loamy and sandy clay would decrease this estimate to be $14,818, sand and gravel would be $14,528, and dense, hard clay would increase this estimate to $18,160. [12]

Dollars per Bank Cubic Yard		10.2
BCY per Cubic Meter		0.7646
Cross-Sectional Area (m^2)		0.7853975
Meters per Mile		1609.34
Total Cost	$	15,981

Table 6: The underlying geometric calculations behind trenching operations at industrial levels. Trenching operations assume "common earth", not including dewatering operations, but including labor and equipment of trenching between 1 and 4 feet deep.

Figure 8: Rail-Mounted Trencher [16]

4.5 Watertight Culvert

To protect cables from damage caused by external fluids, soil, ground faults, or other natural causes, watertight culverts are needed. As per calculations devised by Luke A. Gray [4], for a power transmission of 3000MW, or two 1500MW cables in a bi-pole system, the cable will be laid in concrete culverts of approximately 3-meter inner diameter and flooded to allow for heat dissipation and convection. The culvert will be 10 cm thick to account for approximated hoop stress as detailed in section 3.7, and designed such that the outer approximate diameter is 3.2 meters. The method of placement of concrete will be split into two steps: first, a slip formed base will be used to line the bottom of the culvert, and later precast concrete sections will be placed on top and made watertight with sealant (see Figure 9). Because of the remote location of most tracks where the HVDC cables will be laid, pre-mixed fluid solutions will rarely be an option for the slip form. Federal regulations dictate that pre-mixed concrete must be laid under certain conditions within around two hours of mixing. Therefore, Type I 3000 psi structural concrete will need to be mixed on-site in the largest quantities possible, 5 cubic yards at a time. By using estimates based on these quantities [12] and the geometry of a semi-circular annular ring of the given dimensions, we estimate that slip formed concrete will amount to $137,000 per mile. The other half of the culvert will consist of precast concrete, pre-stressed to the necessary cross sectional geometry and grouted. Because concrete for a precast cover does not need to be mixed on-site, it is considerably cheaper than its slip formed counterpart [12]. In fact, without the equipment and labor costs that slip form has, the cost per mile of precast concrete is only $88,000. In order to transport the concrete on-site in its precast or unmixed forms, the Cable Train would need to be extended by a large number of carts to hold the concrete until it is ready for use. However, an alternative solution is to repeatedly transfer the concrete from an additional platform onto the train from the back, enabling large quantities to be quickly transported on-site without the need for massive holding areas. Such a solution would add significantly less overhead, and allows for more accurate estimation, which includes a transportation cost.

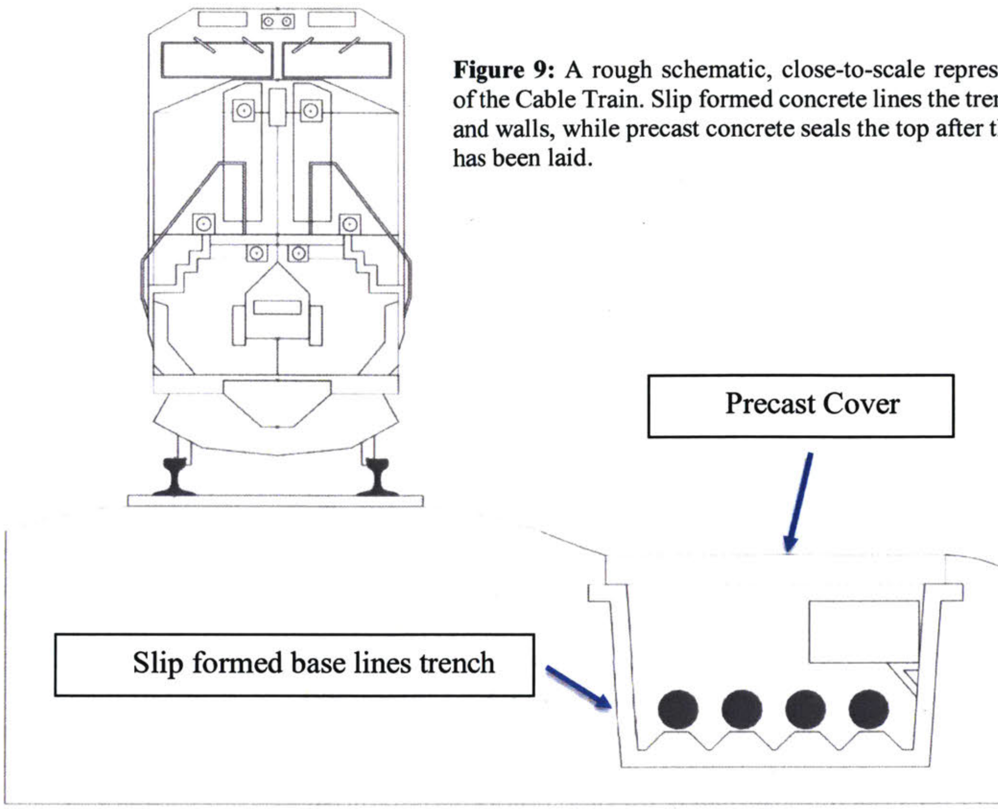

Figure 9: A rough schematic, close-to-scale representation of the Cable Train. Slip formed concrete lines the trench base and walls, while precast concrete seals the top after the cable has been laid.

4.6 Cable Installation

One considerable cost of HVDC cable that must be included in any cable-laying project is the cost of installation. Normally, cable is laid using laborers adhering to federal regulations. For the purposes of the Cable Train, such laborers will not be necessary as the process is automated along with the rolling stock. Conservative estimates based on the use of laborers [12] place this number at 2.2% of the overall project cost per mile, or $59,800 per mile, although it will almost certainly be lower for the train. Another installation cost is that of link boxes, which will need to be placed to provide repair access to the cables and to house certain equipment such as fiber-optic distributed temperature sensing (DTS) devices. In these link boxes, additional resources can be placed, as decided on by future works, for surge protection, seismic activity, etc.

4.7 Heat Dissipation and Fluid Pressure in the Culvert

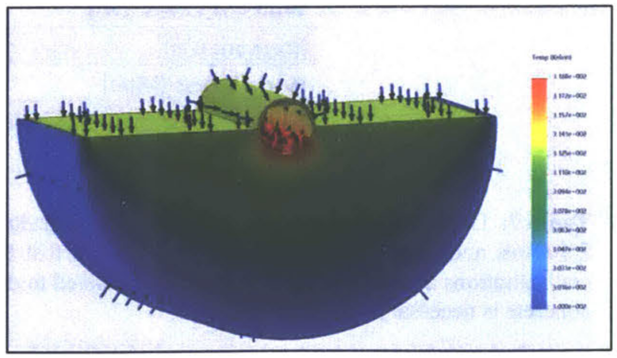

Figure 10: A SolidWorks Simulation of heat dissipation in an HVDC system [4] shows the need to flood or fill the culvert with a material to dissipate heat. An investigation of flooding the pipe was found to need a forced convection flow rate of $0.25 m^3/s$, while a simulation for a backfilled trench is scheduled for future work.

One more cost associated with the ongoing operation of the cable train is enabling heat dissipation from the cables. Because HVDC cable operates at such high voltage and current, it gives off its transmission losses mainly in the form of heat [2]. In order to safely operate at these voltages without compromising the integrity of the cables, the heat given off by convection from the cables must be wicked away by air flowing at a rate of between 0.5-3m/s with a heat transfer coefficient of 16 W/m^2K [4]. Such conditions are possible with the implementation of an air circulation system with periodic blowers along the line; however, using air requires pumps at such short intervals that it is infeasible for such a project. A much simpler, more effective solution is simply to flood the culvert with water. Water's high specific heat will draw excess heat away from the cables much more quickly than air due to its higher heat transfer coefficient, creating less operating costs as once the pipe is flooded, less pumps will need to be used. A typical single-stage, double suction industrial pump can operate at 4000 gallons per minute and 150 horsepower [12]. For a culvert of a 3-meter inner diameter, and a required flow rate of $0.25 m^3/s$ [4], a pressure head of 443,000 Pa is required. In analyzing the hoop strain in the pipe under these conditions, as is shown in Figure 10, the hoop strain of 6.65MPa is well below the threshold of even low quality cement, for example, 2500 psi, 18MPa Type I (although 3000 psi, 20 MPa concrete is used in the cost calculations). The distance between pumps must be 90.86 km, or 56 mi. At this distance and an average cost of $45,400 [12] per pump, the cost per mile is $804. However, unfortunately this cost is not all-encompassing, and a compensation estimate must be made for maintenance and repairs, equating to about 10% of the pump cost, increasing this cost per mile estimate to $900. Furthermore, ongoing costs to operate these pumps will require additional costs due to the energy needed to drive them. According to Prism Engineering's energy cost calculator [25], running a pump of these specifications full time with an efficiency of 0.8 will equate to $55,000 per pump at a standard electrical rate of $0.045 per kWh. For the purposes of the project, this would equate to $982 per mile per year of cable.

Pipe Diameter (m)	3
Wall Thickness (cm)	10
Pressure (Pa)	443000
Hoop Stress (Mpa)	6.65
Max Hoop Stress of Concrete	18

Table 7: The underlying assumptions leading to calculation of hoop stress. For the lowest quality of concrete, 2,500 psi and 18MPa maximum pressure, we see that the culvert under pressure is safe from fracture. Stress concentrations at corners will be further investigated to determine if a higher safety factor is required or if better concrete is necessary.

4.8 Rehabilitation, Commissioning, and Decommissioning

Rehabilitation and cleanup is a vital step of the project, and consists of restoring the land to its previous state as much as possible when a project is completed. The rehabilitation costs of the Cable Train consist of cleaning debris, rubbish, excess soil and brush, etc. Such work does not consist of replanting trees in the 8-meter right of way, as roots are a large risk factor when placed near concrete pipe. According to the compilation of data in RSMeans [12], the cost of rehabilitation and cleaning is generally 0.3-1% of the total project cost, or $27,254 per mile using the more conservative end of this estimate.

Commissioning costs are the costs associated with beginning a project, and can include gaining approval from the state, buying permits, and other project initiation costs. Commissioning costs for a project can vary depending on location, but generally a good guideline is to account for 0.5-1% of the total project cost in commissioning fees [12]. Decommissioning costs, on the other hand, are usually significantly more difficult to estimate as they are very specific to region, terrain, state and federal law, deconstruction equipment, and other factors. However, for the purposes of power transmission, if cables are being replaced, there is also the option of leaving it in the trench or moving it over, significantly reducing or even eliminating decommissioning costs.

4.9 Fuel Consumption Costs

One final operating cost that must be taken into consideration in future is that of fuel consumption. There are two main modes of power consumption while the Cable Train is operating. The most obvious is the cost of fuel that the train takes to move its heavy equipment along the line. The rate-limiting step in the operation of the Cable Train that controls how high this cost gets is the speed at which cable can be extruded and cured. During this process, the train will have to operate at a very slow, but never zero, rate so that the cable can be extruded and eventually laid in the culvert. The other mode of power consumption on the train is the operation of heavy machinery. Using a combination of power estimates for this machinery based on Luke A. Gray's work and the quotes supplied by vendors [4], fuel costs will be around $13,000 per mile.

5. Revenue Under Typical Industry Conditions

Traditional business models in the cable manufacturing industry and power transmission industry rely on a working business relationship between a utility company and cable manufacturer to complete a project. When there is a need for power, a utility company bids on a project and contracts a cable manufacturer to create a cable with the desired specifications to complete the project. Instead of a partnership, the utility will pay to retain ownership of the line, and therefore have the responsibilities associated with ongoing lifetime costs. A typical industry breakdown of the revenue incurred by the cable manufacturer is given in Figure 11 [17]. By doing a cross-analysis of the data provided by Frost & Sullivan (Figure 11 below, a markup of 2.7%) with data provided by RSMeans [12], which provides a profit markup of 5-15%, this data seems fairly low. However, the reason for this discrepancy is due to overruns, underestimates, and various other unforeseeable factors that crop up in every project.

The revenue model for the Cable Train, however, is not simply a projected markup on the costs of the project. Typically, pricing is demand driven and is much more complex and dependent on various external factors decided upon by the market. The issue is further complicated by the fact that the power transmission market is not a highly competitive industry because of the field's high barriers to entry, so the pricing model is not completely demand-driven, but some complicated demand-driven and supply-driven dynamic.

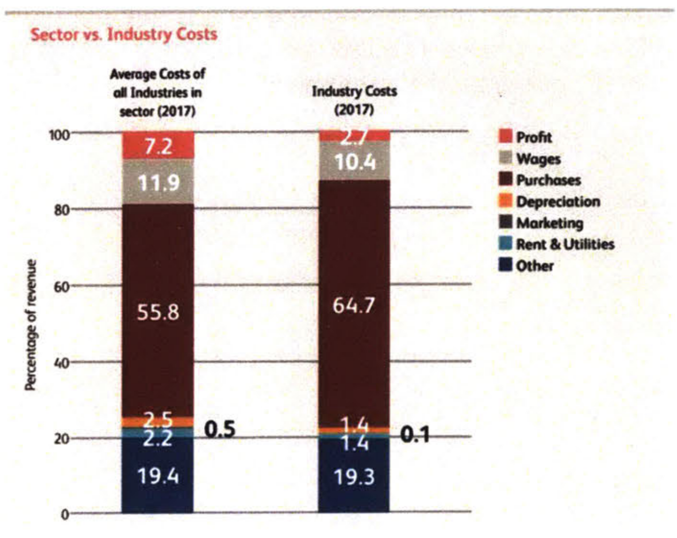

Figure 11: Cable manufacturing industry revenue breakdown provided by Frost and Sullivan [17]. The cable manufacturing industry provides significantly less markup than the sector it exists in (power transmission), and less than the markup provided by RSMeans, indicating a discrepancy in charged rates and actual income.

By working our way backwards from industry and sector breakdowns, we can encompass all of these complicated costs into an inverse model to find a rough estimate of revenue per mile, assuming a model typical of industry. The assumption associated with this model is that the train is owned by a manufacturing company who then sells off the cable to a utility company. By assuming that operating costs comprise the industry average of 64.7% [17], we can deduce that revenue should be on the scale of $15.6 million per mile. Profit, however, will be a fraction of this, resulting in approximately $422,000 per mile with this economic model (as defined in section 2).

6. Overall Cost and Profitability

When comparing the Cable Train's cost-efficiency to that of overhead lines and HVAC cables, a number of other factors come into play. As discussed earlier, HVAC transmission lines have higher losses over large distances, making them unfeasible for larger projects. As is always the case when comparing HVAC to HVDC, the concept of a "break-even" distance crops up. The "break-even" distance is the length a cable must be for the HVAC transmission losses to be high enough where HVDC becomes more cost-efficient (see Figure 12), and therefore for a given power transmission rate, more profitable. In the case of the Cable Train, this should occur after about 70-107km according to one source [18], while another claims this value is closer to 40-50km [11]. To apply these distances to the Cable Train, the smallest case studies which were compared in this project were, at a minimum, 150 miles, or 240km long. In an ideal scenario, for a project such as Three Gorges Dam, transmitting the power from the dam to the high-demand East coast areas would be closer to 1100km. For a project of this scale, an HVAC solution does not appear to be plausible, whereas an HVDC line could be economical.

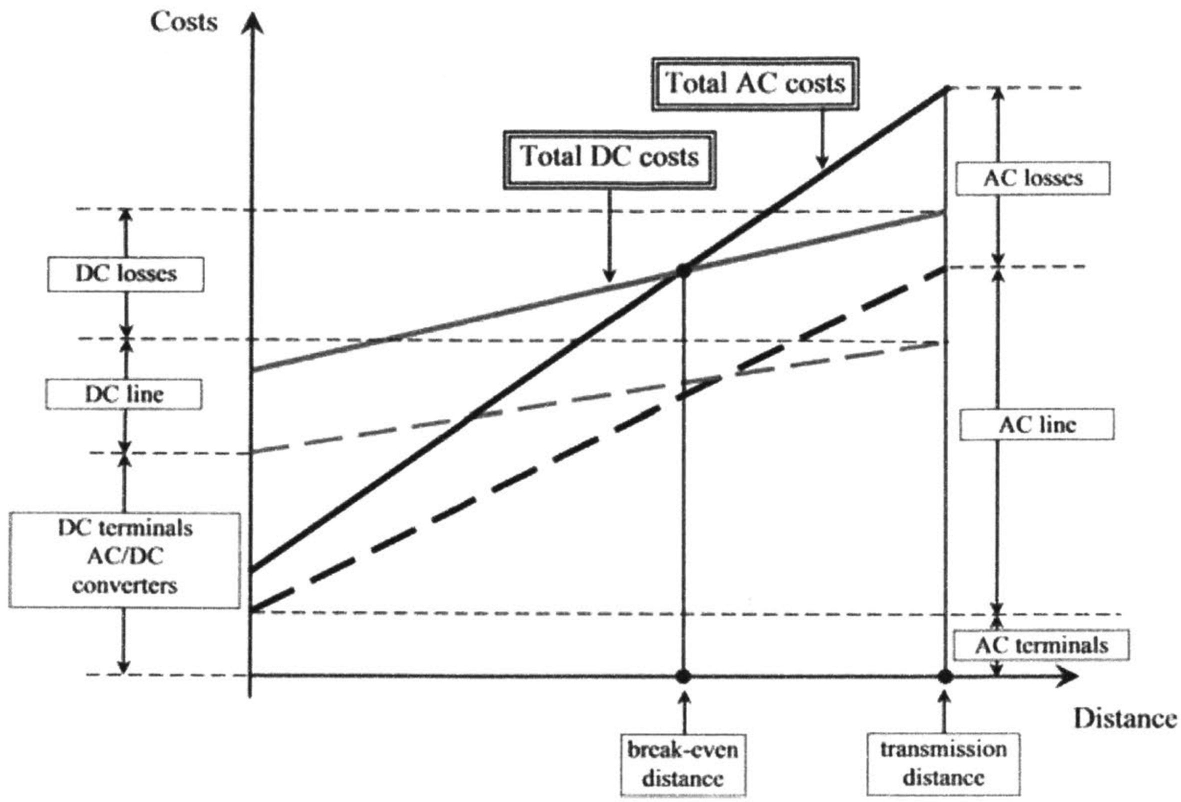

Figure 12: A cost vs. distance analysis for DC and AC cables [11] demonstrates the concept of a break-even distance past which DC costs become increasingly less. Factors that go into this calculation include terminals and converters as a fixed cost, and the cost of the line and losses as costs scaling with the length of the cable. While DC overhead costs are higher initially, their variable costs are lower, leading to this eventual break-even distance.

To find an all-encompassing estimate for the ongoing project costs associated with a certain length of cable, data from all these various sources and estimates has been put in a spreadsheet. In addition to the costs discussed previously, two additional costs may be added when completing a project. First, at some points in the project, depending on terrain, it may become necessary to extend the right of way embankment in order to get heavy equipment to a location. Land-settling estimates can vary, but considering most right of way on Cable Train projects is expected to be on public land, settling can be estimated to be $6.55 per square foot [12]. Similarly, another cost associated with individual projects will be how many viaducts will be necessary to span rivers, roads, or other terrain. Additional reinforcement estimates should be taken into account for such estimates as the existing tracks will not likely be able to support the cable and its culvert. These costs will be non-negligible, but cannot be added without project specifications, and so are left as additional line items to be added once project specs are finalized. Under the final assumption that the project requires two cables in a bi-pole system for a total capacity of 3000MW, the total operating cost per mile of the Cable Train is $2.8 million. Table 8 holds additional relevant conditions and assumptions of the cost breakdown.

Work Tasks	*Condition*	*Per Mile Cost*	
Surveying	Topographical Surveying, conventional, maximum (Material + Labor + Equipment)	$	4,291
Clearing	Clear and Grub Brush inc. stumps up to 12", labor and equipment inc.	$	8,727
Rubbish/debris Removal	10 Ton Capacity	$	127
Trenching	Common Earth with no Sheeting or dewatering included, 1' to 4' deep (Labor + Equipment), 3/4 cubic yard excavator	$	15,981
Slipform	Concrete, Volumetric Site-mixed, includes local aggregate, sand, Portland cement (Type I and water), 3000psi, 5 cubic yard, (Material)	$	136,756
Cable Cost	Average of Cables Rated to 3000MW, 4 cables	$	2,410,974
Cable Installation	Applied Science	$	59,806
Precast Cover	Precast Slab Plank, prestressed, grouted, solid, 4" thick (10cm), (Material + Labor + Equipment)	$	87,995
Pumps	Single Stage, double suction domestic water pumps (Material + Labor), 150HP, up to 4000 Gallons per Minute	$	804
Commisioning	Systems Operation and verification during turnover including all systems subcontractors, Systems Design Assistance, operation, verification and training	$	27,255
Rehabilitation/Cleaning	After Job Completion, allow: Maximum	$	27,255
Fuel Consumption	Energy to move the train, consumption of machinery included	$	13,049
	Total Sum	**$**	**2,793,019**

Table 8: The summed operations of all of the operating costs associated with the Cable Train, as well as the conditions and assumptions made to draw estimates. This snapshot gives a relative estimate of the costs of each operation of the process.

In order to draw a proper comparison to other projects, we must first account for the transmission power of the project, which will vary depending on location and needs. By doing so, we see that the operating cost of the Cable Train is $931 per mile per MW of power required. By comparing this cost to the cost of other projects (see Table 9), we can compare the cost efficiency of the Cable Train. Again normalizing by power, we can see that the Northern Pass and New England Clean Power Link projects cost $6,250 and $8,000 per mile, respectively. Similar cost estimates can be shown for the other projects. Even under very conservative assumptions and with a safety factor as high as 6, the Cable Train provides a viable, efficient solution to the power needs of these areas, beating them by a wide margin in terms of cost.

Alternative	**Northern Pass** (Northeast Utilities and Hydro-Québec)	**New England Clean Power Link** (Transmission Developers Inc.)	**Champlain Hudson Power Express** (Transmission Developers Inc.)	**Northeast Energy Link** (National Grid, Emera)	**Conceptual New Hampshire Burial Alternative** (White Paper)
Key Elements	• Conduit for 1200 MW of power from Hydro-Québec to ISO-NE market • 187 miles of new HVDC/HVAC transmission lines in New Hampshire • 180 miles of overhead lines, 7.5 miles of underground lines • 10 miles of new and relocated transmission lines in White Mountain National Forest • HVDC converter station in Franklin	• Conduit for 1000 MW of power from Canadian sources (likely Hydro-Québec) to central VT • 150 miles of buried HVDC transmission lines in Vermont • 100 miles of underwater HVDC transmission lines in Lake Champlain • 50 miles of underground HVDC transmission lines buried in roads or transmission corridors • HVDC converter station in Ludlow, VT	• Conduit for 1000 MW of power from Canadian sources (likely Hydro-Québec) to NYC area • 333 miles of buried HVDC transmission lines in eastern New York • 133 miles of underground HVDC transmission lines buried in active transportation corridors (rail and roads) • HVDC converter station in NYC • $117m environmental trust fund	• Conduit for 1100 MW of power from Canadian and northern/ eastern Maine sources to Massachusetts • 230 miles of underground HVDC transmission lines in designated corridor (I-95) • Two converter stations • To include AC upgrades to collect northern/ eastern Maine-based wind energy	• Similar length and configuration as Northern Pass HVDC portion • Conduit for 1100 MW of power • Buried transmission lines with preferred use of softened corridor • Several routing alternatives, including interstate highways, railroad ROWs, and existing Phase II HVDC transmission corridor
Estimated Costs	• $1.4 billion total • Overall project cost per mile: $7.5m • Burial costs: *$13m/mile*	• $1.2 billion total • Overall project cost per mile: $8m • **Burial costs: TBA**	• $2.2 billion total • **Burial costs: $5.4m/mile**	• $2 billion total • **Burial costs: $5.7m/mile**	• $2 billion total • **Burial costs: $5.3m/mile**

Table 9: Conservative Law Foundation (CLF) compares the costs of several projects in the northeastern United States and Canada and compares them [19]. Their estimated costs are a combination of actual underground cable costs and predicted costs if planned/existing overhead were to be converted to underground cables. In a normalized comparison with the Cable Train, the costs of the Cable Train are at least 6.7 times less.

7. Discussion of Potential Business Models

The business model for the Cable Train will vary depending on the companies and states involved. Currently, a common business model is for utility companies to buy and maintain transmission lines after they have been commissioned. In this case, the developer is the sole proprietor of the train and must raise the capital to develop the train in the first place, and then operate it. After development, the Cable Train begins operation on other projects before turning over line maintenance and operation to the utility company. In this scenario, the capital costs of the Cable Train will be the most difficult obstacle to overcome, but will be amortized as time goes on and projects are completed.

A second model is that of a state-owned Cable Train, as would almost certainly be the case in China. In such a model, where the state is in charge of the development, operation, and ownership of the train, funding would be less difficult. If the state deems the train fit for operation as a solution to its energy-disparity problems, it could fund the project and get it off the ground. As far as ongoing operation of the train, the state would be able to decide when and where to send it to maximize benefits to the country. In the US, Brazil, or the EU, for example, government agencies could fund the research to bring the Cable Train to prototype test phase (TRL-7) at which point venture investment or partnering with existing rail car development companies would bring the project to the ready to deploy phase (TRL-9).

The fastest path forward would likely be that of a joint partnership between utilities, railroads, utilities, and private equity firms. Such a business model would benefit from the support of external sources of funding, but care would have to be taken to avoid internal politics. The complicated details of a revenue and profit modelling would need to be worked out by the companies involved, and would depend heavily on which companies are the most risk-averse.

8. Conclusions and Recommendations

In summary, between the technological proof-of-concept outlined in "Cable Train: A Mobile Platform for Manufacturing and Installing UGC Transmission Systems" and the cost estimation presented here, it is maintained that the Cable Train may provide a significant opportunity for reducing the cost of laying long-distance HVDC cable for bulk power transmission. With the advent of enabling technologies and a world-wide venture to develop clean energy generation, the Cable Train is the next step forward in realizing the goal of a large, robust HVDC system for sharing renewable energy. With the overall cost per mile of a typical project being estimated at $2.8 million per mile, and the cost per transmission capacity rate of the Cable Train being estimated at a fraction of current projects, the Cable Train deserves further investigation.

Further work should be done in a number of areas, both to assess the technological validity of the project and the economic viability. Revenue and profitability for the purposes of this project have been considered under the most basic economic model, that of a proprietor transitioning the cable to a utility. However, to truly grasp the potential of the Cable Train, further work should be done to model the viability of both a state-run system and one funded and run by a conglomerate of independent companies. Our recommendation that the fastest path forward is most likely by garnering support from a number of companies stems from a basic understanding of funding and should be taken with some reservation. With enough support from one proprietor, a single interested company, the Cable Train could gain the necessary funding to operate under a single company as well. In such a scenario, our economic model should sufficiently reflect how the operations will unfold. In the case of a state-sponsored Cable Train, the Cable Train would likely gain very little traction in the U.S. due to internal politics, while we would strongly recommend such a model for China. Within our costing analysis, so-called "first-costs" were considered due to their direct influence over and impact on the initial costs of the Cable Train, but further work is required in more detail about the life-time costs of the cables laid. Some of these life-time costs may include more detailed analysis of permitting and legal costs, transmission power loss costs, lifetime maintenance costs, and environmental costs. Project-specific costs will add line-items to this estimate and should be taken into close consideration as well.

The future of the Cable Train not only exists in its technology or profitability, but also in the continued future development of a renewable energy grid. Future work done by Luke A. Gray and Professor Alexander H. Slocum will include work based off of a study by Alexander E. MacDonald and Christopher T.M. Clack et al. [29] showing that an optimized HVDC grid could be created using a combination of railroad lines and weather data to connect high areas of renewable energy in the U.S. (e.g. solar in the south-west, wind across the plains) to regions of high demand. According to MacDonald et al. connecting these resources via the railroad grid could eliminate up to 80% of CO2 emissions, while maintaining the same cost of electricity and energy needs as 2012 [29].

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