PJM Interconnection
Potomac-Appalachian Transmission Highline (PATH) Project

HVDC Conceptual Study

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1.0 Executive Summary

The Potomac-Appalachian Transmission Highline (PATH) Project includes construction of a new EHV interstate transmission line between American Electric Power (AEP) and Allegheny Power within the PJM electric transmission system. The transmission line is approximately 276 miles in total length with approximately 225 miles in West Virginia, 31 miles in Virginia, and 20 miles in Maryland. The transmission line will interconnect the existing Amos substation to the proposed new Welton Spring and Kemptown substations. The PATH Project expected in-service date is currently June 2014.

The PATH Project is currently proposed to be a single circuit 765kV AC overhead transmission line for the entire route which is referred to as the base design in this document. PJM has requested Black & Veatch (B&V) assistance to develop an HVDC Conceptual Study considering the following two alternate technology options: 1) HVDC transmission with overhead conductors for the entire route; and, 2) a hybrid of HVDC transmission with underground cables and AC transmission with overhead conductors. B&V has enlisted the assistance of Asea Brown Boveri (ABB) to develop the HVDC portion of the Study.

A summary of the terminology used in this Study is included in Section 2.0.

B&V together with ABB have proposed the following two concepts for the PATH Project:

1. Concept 1: Bipolar ±600kV HVDC, 2×2000 MW overhead thru transmission from Amos to Kemptown with a Bipolar ±600kV HVDC, 2×1000 MW tap at Welton Spring.

2. Concept 2: A hybrid of single circuit 765kV AC overhead transmission from Amos to Welton Spring with Symmetrical 800kV (±400kV) HVDC, 3×1333 MW solid-dielectric underground transmission from Welton Spring to Kemptown.

Concept 2 is based on utilizing XLPE cable rated for 400 kV HVDC. This new technology is currently being developed by several manufacturers; therefore, there is some risk, that this new technology may not be available to support the in-service date for the PATH Project. ABB does expect to have the first XLPE cable system qualified for commercial use at 400kV HVDC in 2011 which will support the PATH Project in-service date.

B&V and ABB have developed conceptual designs and Cost Estimates for Concept 1 and Concept 2. To provide a basis for comparison, B&V has also
developed Cost Estimates for the Base Design. The conceptual designs and detailed summaries of the Cost Estimates are included in the Appendices.

The Cost Estimates developed as part of this study are summarized below.

Base Design from Amos to Welton Spring

AC Overhead Line - $756 Million

Base Design from Welton Spring to Kemptown

AC Overhead Line - $448 Million

**Base Design TOTAL - $1204 Million**

Concept 1 from Amos to Welton Spring

HVDC Overhead Line - $634 Million
HVDC Converter Station at Amos - $300 Million
Subtotal - $934 Million

Concept 1 from Welton Spring to Kemptown

HVDC Overhead Line - $368 Million
Overhead Tap DC Switchyard at Welton Spring - $8 Million
HVDC Converter Stations at Welton Spring - $238 Million
HVDC Converter Stations at Kemptown - $300 Million
Subtotal - $914 Million

**Concept 1 TOTAL - $1848 Million**

Concept 2 from Amos to Welton Spring

AC Overhead Line - $756 Million
Subtotal - $756 Million

Concept 2 from Welton Spring to Kemptown

HVDC Underground Line - $884 Million
HVDC Converter Stations at Welton Spring – $696 Million
HVDC Converter Stations at Kemptown - $696 Million
Subtotal- $2276 Million

**Concept 2 TOTAL - $3032 Million**
The Concept 1 and Concept 2 Cost Estimates herein do not include the AC substation interconnection facilities. For relative comparison purposes, the AC substation interconnection facilities estimated costs are included in the cost comparison summaries included in Section 7.0.

For all Cost Estimates, it was assumed that the siting, routing, permitting, and land acquisition costs will be estimated by others. AEP or Allegheny Power indirect costs are not included in the Cost Estimates. Specific details for all assumptions are included in the subsections of this Study.

All Cost Estimates are in US dollars and are based on 2009 commodity prices and cost of labor and do not include any market or commodities escalation. The Cost Estimates for the HVDC converter stations and underground cables are based on a currency exchange rate of 7.5 Swedish Kronor per US dollar.

It is hereby understood that neither the Cost Estimates, its associated commercial terms nor any past or future action, course of conduct or failure to act by either Black & Veatch, ABB, or PJM regarding the PATH Project will give rise to or serve as a basis for any obligation or other liability on the part of the parties or any of their affiliates. Neither party shall be obligated to enter into any further agreement with another party. Any commitment, agreement or binding obligation with respect to the PATH Project would only arise and would be subject to, among other things, the negotiation, the due execution and delivery by the parties of a Definitive Agreement regarding the Path Project.
2.0 Introduction
For the purposes of this Study, the following terms have the following meanings. The meanings specified are applicable to both singular and plural.

“AC Overhead Line” means single circuit 765kV AC overhead transmission line.

“Base Design” means the AC Overhead Line concept currently proposed for the PATH Project.

“Bipolar” means a double circuit HVDC transmission line with the + pole and the metallic return comprising one circuit, and, the – pole and the metallic return comprising the second circuit.

“Circuit” means an independent set of parallel transmission line conductors, e.g. “single circuit” means a single set of three phase conductors which comprises a circuit on an AC overhead transmission line; or, a single set of one HVDC pole conductors (+ or -) and a metallic return conductor which comprises a circuit on the HVDC overhead transmission line.

“Concept 1” means the HVDC conceptual design concept as defined herein.

“Concept 2” means the HVDC conceptual design concept as defined herein.

“Cost Estimate” means Engineering, Procurement, and Construction (EPC) indicative cost estimate.

“GIL” means gas insulated line (cable).

“HDD” means horizontal directional drilling.

“HPFF” means high pressure fluid filled (cable).

“HVDC Overhead Line” means the Bipolar ±600kV HVDC overhead transmission line proposed for Concept 1.

“HVDC Underground Line” means the triple circuit Symmetrical 800kV (±400kV) HVDC underground transmission line proposed for Concept 2.

“HVDC” means high voltage direct current.

“LCC” means Line-commutated Current-source Converter.
“MI” means mass impregnated (cable).

“PATH Project” means the Potomac-Appalachian Transmission Highline Project.

“SCFF” means self contained fluid filled (cable).

“Symmetrical” means a single circuit mid-point grounded HVDC system.

“Study” means the HVDC Conceptual Study.

“VSC” means self-commutated Voltage-Source Converter

“XLPE” means Cross-Linked Polyethylene (cable).

The currently proposed Potomac-Appalachian Transmission Highline (PATH) Project consists of approximately 276 miles of AC Overhead Line to be constructed in West Virginia, Virginia and Maryland from the existing Amos substation in Putnam County, West Virginia to the proposed new Kemptown substation in Frederick County, Maryland. The PATH Project also includes a proposed new substation in Hardy County, West Virginia called Welton Spring. The PATH Project will be designed and built by Potomac-Appalachian Transmission Highline, LLC, a Joint Venture between American Electric Power (AEP) and Allegheny Power.

The PATH Project is needed to ensure the reliable operation of the PJM electric transmission system and is primarily needed to resolve significant forecasted thermal overload and reactive reliability criteria violations. The PATH Project’s expected in-service date is currently June 2014 and PJM has forecasted significant and numerous violations of the NERC Reliability Standards as early as June 1, 2014, if the PATH Project is not completed on schedule.

In May 2009 applications for Certificates of Public Convenience and Necessity (CPCN) for the PATH Project were filed with the Public Service Commission of West Virginia, Maryland Public Service Commission, and Virginia State Corporation Commission. Pertinent information from the CPCN filings was used as a basis for the Cost Estimates for the Base Design and the AC interconnection substations.

PJM has requested Black & Veatch (B&V) assistance to develop an HVDC Conceptual Study considering the following two alternate technology options for the PATH Project: 1) HVDC transmission with overhead conductors for the entire route; and, 2) a hybrid of HVDC transmission with underground cables and AC transmission with overhead conductors.
B&V together with ABB have considered three concepts for the PATH Project which are listed below. Block diagrams for these three concepts are included in Appendix A of this Study.

1. Concept 1: Bipolar ±600kV HVDC, 2×2000 MW overhead transmission from Amos to Kemptown with a Bipolar 2×1000 MW tap at Welton Spring.

2. Concept 2: A hybrid of single circuit 765kV AC overhead transmission from Amos to Welton Spring with Symmetrical 800kV (±400kV) HVDC, 3×1333 MW solid-dielectric underground transmission from Welton Spring to Kemptown.

3. Concept 3: Symmetrical 800kV (±400kV) HVDC, 3×1333 MW overhead transmission from Amos to Welton Spring and Symmetrical 800kV (±400kV) HVDC, 3×1333 MW underground transmission from Welton Spring to Kemptown.

Concept 1 is based on HVDC overhead transmission and Line Commutated Converter (LCC) technology. The ultimate 4000 MW transmission capacity between Amos and Kemptown will be installed in 2000 MW units arranged in a Bipolar configuration at each HVDC converter station. One unit will provide the positive pole and the other will provide the negative pole with a common neutral. Each of the poles will create a separate circuit with the positive (+) pole or negative (-) pole conductor and a shared metallic return conductor on the HVDC Overhead Line. The HVDC converter station tap at Welton Spring will be installed in 1000 MW modular units arranged in a Bipolar configuration. An HVDC switching station at Welton Spring will be provided to allow for segregation of the HVDC Overhead Line circuits for outages and maintenance.

Concept 2 is based on HVDC underground transmission and Voltage-Source Converter (VSC) technology for the segment between Welton Spring and Kemptown and an AC Overhead Line for the segment between Amos to Welton Spring. The ultimate 4000 MW transmission capacity between Welton Spring and Kemptown will be provided by three 1333 MW rated modular VSC HVDC converter stations and an HVDC Underground Line comprised of three separate and parallel HVDC underground cable circuits.

Concept 3 is based on Voltage-Source Converter (VSC) technology with HVDC overhead transmission for the segment between Amos to Welton Spring, and HVDC underground transmission for the segment between Welton Spring and Kemptown. The ultimate 4000 MW transmission capacity between Amos and Welton Spring and between Welton Spring and Kemptown will be installed with 1333 MW rated modular VSC HVDC converter stations and three separate parallel circuits per segment.
During the development of the Study, B&V and ABB submitted three Block Diagrams included in Appendix A of this Study to PJM for preliminary review and discussion. The Block Diagrams identified that in order to match the three circuits required to transfer the power using underground transmission, Concept 3 will require three separate overhead transmission circuits for the segment between Amos and Welton Spring, thus raising relative costs without providing significant benefits as compared to Concept 1. Therefore, it was agreed by all parties to focus the detailed study on Concepts 1 and Concept 2. Concept 3 was not studied in detail but is included for reference only in this Study.

B&V and ABB have developed conceptual designs and Cost Estimates for Concept 1 and Concept 2. The conceptual designs are included in the Appendices and the details of the Cost Estimates are included in the subsections of this Study.

To provide a basis for comparison, B&V has also developed a Cost Estimate for the Base Design using the same assumptions as the HVDC Overhead Line concept as well as pertinent information from the CPCN filings. Also for relative comparison purposes, the AC interconnection substation facilities estimated costs from the CPCN filings are included in the cost comparison summaries included in Section 7.0 of this Study.

2.1 Project Requirements

During the development of the Study, PJM advised that the AC Overhead Line requires a 5000 MVA thermal capacity between Amos and Kemptown; however, since the HVDC Overhead Line is a purely resistive circuit, only 4000 MW thermal capacity is required between Amos and Kemptown to provide similar PJM AC grid reliability performance. PJM also advised that a 2000 MW thermal capacity will be sufficient to be injected at Welton Spring for Concept 1. Based on these requirements, ABB provided recommendations regarding the optimum HVDC technology to utilize for the concepts studied. Details of the two technologies currently available are included in Section 3.0 of this Study. These two technologies include Line Commutated Converter (LCC) and Voltage Source Converters (VSC). Specific details on the selection of the HVDC technology are included in Section 3.3 of this Study.

PJM confirmed that black-start capability and static synchronous compensator (STATCOM) support are not required for the PATH Project.

PJM has advised that the HVDC converter stations need to be able to absorb reactive power. ABB advised that the VSC technology has both +/- reactive support capability and that the LCC technology requires its own reactive support via switchable shunt capacitor/filter/reactor banks. Details of the differences between these two HVDC technologies are included in Section 3.0 of this Study.
PJM advised that the AC interconnection voltages will be as follows:

- Amos: 765kV
- Welton Spring:
  - 500kV if the HVDC transmission line starts at Amos
  - 765kV if the HVDC transmission line starts at Welton Spring
- Kemptown: 500kV

PJM advised that fluid filled cable technology should not be considered for any water crossings.

PJM advised that the available fault current at Amos 765kV is 34.9 kA (3-phase) and 34.4 kA (single-phase). The available fault current drops down to 27.4 kA (3-phase) and 27.6 kA (single-phase) with the Amos to Culloden 765kV transmission line (strongest source) out of service. At Kemptown, the available 500kV fault current is 29 kA (3-phase) and 22 kA (single-phase). With the Doubs to Kemptown 500kV transmission line out of service, the available fault current drops down to 18.3 kA (3-phase) and 13.9 kA (single-phase). For Welton Spring, the available fault current on the 500kV side is 21.3 kA (3-phase) and 18.7 kA (single-phase). With the Welton Spring to Mt. Storm transmission line out of service, the available fault current drops down to 7.4 kA (3-phase) and 7.1 kA (single-phase). All of the fault current data was derived from PJM’s short circuit model assuming the Amos to Welton Spring to Kemptown AC Overhead Line is out of service to reflect an HVDC transmission line for short circuit studies. The fault study information is required to determine the proper HVDC technology to utilize since the LCC technology requires a minimum short circuit capacity (in MVA) ratio of 2.5 times the HVDC converter station power rating for reliable operation. Specific details of this requirement are included in Section 3.0 of this Study.

2.2 Route Description

The Study is based on the proposed general route shown on the Estimated Route for Transmission Map included in Appendix C of this Study.

It was assumed for cost estimating purposes that the route for either the overhead transmission line or the underground transmission line will be the same. A detailed survey will be required during actual design to confirm the technical viability of the routes and any surface terrain or underground challenges that may require mitigation.
The route from Amos to Kemptown is approximately 276 miles in total length and is comprised of the following segments:

- 225 miles in West Virginia
- 31 miles in Virginia
- 20 miles in Maryland
- 176 miles from Amos to Welton Spring
- 100 miles from Welton Spring to Kemptown.

The GPS coordinates of the proposed new Welton Spring and Kemptown substation are as follows:

**Welton Spring**
Latitude: N39° 10.71’
Longitude: W78° 56.472’

**Kemptown**
Latitude: N39° 21.516’
Longitude: W77° 13.612’
3.0 HVDC Converter Stations

HVDC transmission is widely recognized as advantageous for long-distance bulk-power delivery and asynchronous interconnections. Unlike an AC transmission system, the power flow on an HVDC transmission system is not affected by phase-angle differences between AC grid buses and can always be maintained at the level determined by economic dispatch. Because of its inherent power flow control, an HVDC transmission system cannot be overloaded due to AC grid contingencies and resulting power surges. There are numerous examples in both North-America and elsewhere where HVDC transmission systems were the only interconnections that withstood cascading AC grid outages and remained in service after system wide disturbances. On the other hand, unlike an AC transmission system, an HVDC transmission system does not inherently take part in re-dispatch of load in connection with fault clearing and other AC grid contingencies. HVDC transmission systems are regularly provided with special controls that allow the AC grid operator to preset desired HVDC re-dispatch in response to transmission line outages or other severe contingencies in the AC grid.

More recently, new cable technology and HVDC converter station designs have broadened the potential range of HVDC transmission system applications to include long distance underground transmission, economic replacement of reliability-must-run generation, and voltage stabilization.

There are two principal converter technologies commonly employed in modern HVDC transmission systems: i.e., line-commutated current-source converters and self-commutated voltage-source converters. Figure 3.1 shows a simplified single-line diagram for a typical line-commutated current-source converter station and Figure 3.2 shows a simplified single-line diagram for a typical self-commutated voltage-source converter station.
Figure 3.1 Typical line-commutated current-source converter station

Figure 3.2 Typical self-commutated voltage-source converter station
3.1 Characteristics of Line-Commutated Current-Source Converters

Most of the world’s existing HVDC transmission systems employ line-commutated current-source converters with thyristor valves. Such line-commutated converters (“LCCs”) require a three-phase synchronous voltage source in order to operate.

The basic building block used for LCCs is a three-phase six-pulse bridge (Graetz Bridge). Each Graetz bridge is comprised of six controlled switching elements or thyristor valves. Each thyristor valve, in turn, is comprised of a suitable number of series-connected thyristor modules to achieve the desired DC voltage rating.

Modern HVDC transmission systems utilize twelve-pulse LCCs to reduce the harmonic filtering requirements. A twelve-pulse LCC consists of two six-pulse thyristor valve bridges connected in series with 30 degrees phase displacement between the AC source voltages. In 12-pulse operation, the characteristic AC current and DC voltage harmonics have frequencies of 12n±1 and 12n, respectively. The 30 degrees phase displacement between the AC source voltages for the two Graetz bridges is typically achieved by feeding one bridge through a transformer with a wye-connected secondary and the other bridge through a transformer with a delta-connected secondary. Figure 3.3 shows the thyristor valve and transformer arrangement for a typical twelve-pulse LCC with three quadruple valve mechanical structures, one for each AC phase. Within each quadruple valve, the thyristor valves are built-up with series-connected thyristor modules.

![Figure 3.3: Thyristor valve and transformer arrangement for a typical twelve-pulse LCC](image-url)
Robust LCC commutation and reliable AC grid performance require connection to a relatively strong synchronous AC source voltage. (Commutation is the transfer of current from one phase to another in a six-pulse thyristor valve bridge.) Experience from earlier AC grid planning and HVDC application studies show that reliable and robust performance of LCC based HVDC transmission systems typically requires post-contingency (N-1) three-phase symmetrical short-circuit capacity at the AC grid interconnection point (in MVA) of at least two-and-a-half to three times the MW power capacity rating of the HVDC converter station. (The LCC itself does not add significantly to the AC grid’s short circuit level.) If such minimum amount of post-contingency short-circuit capacity is not available, a conceptual HVDC design study must consider either reinforcement of the AC grid at the HVDC converter station interconnection point or application of self-commutated voltage-source converter HVDC technology.

In case the AC grid voltage at the receiving end of an LCC based HVDC transmission system suddenly drops (e.g., due to a ground fault on a nearby AC transmission line), the normal commutation process between thyristor valves in the LCC may fail and the HVDC transmission system will experience a commutation failure. A commutation failure is ‘self-healing’ but disrupts temporarily the power transmission on the HVDC transmission system. (The HVDC controls typically restore full HVDC power transmission within 100-200 milliseconds.) Since both poles in a LCC based Bipolar HVDC converter station are connected to a common AC grid voltage, commutation failures are typically Bipolar events.

LCCs can only operate with the AC current lagging the voltage: i.e., the LCC conversion process demands supply of reactive power. In an LCC based HVDC converter station, the LCC’s reactive power demand is typically supplied from AC harmonic filters (which look capacitive at the power frequency) and shunt capacitor banks. (The AC harmonic filters and shunt capacitor banks are an integral part of the HVDC converter station design.) Any surplus or deficiency in reactive power supply from the HVDC converter station must be accommodated by the AC grid.

Any imbalance between the reactive power supplied by the HVDC converter station’s AC harmonic filters and shunt capacitors and the reactive power consumed by the LCCs needs to be kept within a specified range to maintain the AC grid voltage within acceptable limits. Generally, the lower the short circuit capacity of the AC grid interconnection point is, or the further the LCC is away from generation, the tighter the reactive power exchange with the AC grid must be maintained to control the AC grid voltage. Figure 3.4 illustrates the reactive power demand, reactive power compensation, and reactive power exchange with the AC grid for a typical LCC-based HVDC converter station as a function of DC power transfer.
Reactive power demand, reactive power compensation, and reactive power exchange with the AC grid at a typical LCC-based HVDC converter station.

Full load power losses for new LCC based HVDC converter stations typically range between 0.65 and 0.75 percent.

The power transfer level and power direction on an LCC-based HVDC transmission system is controllable between its minimum power (typically 10% of rated power) and its rated power. Basic power control is considered a dispatch function to accommodate scheduled power flows with selectable ramp rates (typically adjustable between 1 to 100 MW per minute) to match changes in generation schedules. LCC-based HVDC transmission systems can also be equipped with fast acting power control functions to improve stability margins in the AC grid through DC power modulation and immediate adjustments to the DC power transfer in response to AC grid contingencies and disturbances.

### 3.2 Characteristics of Self-Commutated Voltage Source Converters

Since the late 1990s, an increasing number of new HVDC transmission systems world-wide have employed self-commutated voltage-source converter (“VSC”) technology. The basic building block for VSC-based HVDC technology is the insulated-gate bipolar transistor (“IGBT”) valve and pulse-width modulation. Since the introduction in the 1990s, IGBT valve technology and VSC-based HVDC transmission systems have been applied at increasingly higher voltage and power capacity ratings, essentially mirroring the rapid development of thyristor valve technology and LCC-based HVDC transmission systems in the 1970s and 80s.

VSC-based HVDC transmission systems can rapidly control both active and reactive power supply to the AC grid independently of one another. (Unlike LCC units, the VSC units themselves have no inherent reactive power demand and can both supply and absorb reactive power.) This VSC characteristic, in turn,
can be utilized to provide dynamic and continuous voltage support to the AC grid similar to that provided by local generators. As illustrated in Figure 3.5 below, VSC-based HVDC converter stations have P-Q capability curves that are similar to large generators and synchronous machines.

![Figure 3.5 Typical P-Q capability curve for VSC-based HVDC stations](image)

Since there are no requirements for minimum short-circuit capacity at the AC grid interconnection point, the process of integrating and locating a VSC-based HVDC converter station in the AC grid is generally much more flexible than for an LCC-based HVDC converter station. As long as the AC grid interconnection point has sufficient thermal capacity to receive or deliver the power, VSC-based HVDC converter stations can be located virtually anywhere in the AC grid. For example, underground HVDC transmission lines and VSC-based HVDC converter stations can become a practical solution to complex and sometimes conflicting AC grid planning requirements, including public opposition to overhead transmission construction, increased energy imports from renewable and remotely located generation, retirement of old and inefficient reliability-must-run (“RMR”) generators, etc. Also, the self-commutation with VSC technology permits black start; i.e., a VSC-based HVDC converter station can be used to synthesize a balanced set of three-phase voltages like a virtual synchronous
generator. Figure 3.6 shows a typical IGBT valve arrangement for a VSC-based HVDC converter station.

Figure 3.6 Typical IGBT valve arrangements in a VSC-based HVDC converter station

Full load power losses for new VSC based HVDC converter stations typically are around one percent.

There are no commutation failures in VSC-based HVDC converter stations and the dynamic AC grid voltage support at each VSC-based HVDC converter station can be used to improve the voltage stability of the AC grid. Also, as for LCC-based HVDC, VSC-based HVDC transmission can be equipped with fast acting power control functions to improve stability margins in the AC grid through DC power modulation and immediate adjustments to the DC power transfer in response to AC grid contingencies and major disturbances.

3.3 Conceptual Designs

3.3.1 HVDC Overhead Line from Amos to Welton Spring to Kemptown – Concept 1

In this Study, the first conceptual design option for the PATH Project includes HVDC transmission construction with overhead conductors for the entire route from Amos to Welton Spring to Kemptown. After consultation with PJM, it was determined that a 4,000 MW continuous power capacity rating for the HVDC converter stations will provide similar AC grid reliability performance as the Base Design proposed in the current PJM transmission expansion plan. Accordingly, Concept 1 in this Study is based on a continuous 4,000 MW power capacity rating for the HVDC Overhead Line for the entire length from Amos to Kemptown.
The highest capacity HVDC overhead transmission line in-service in the United States to-date is the Pacific Intertie overhead transmission line between Oregon and southern California, which is rated 3,150 MW at ±500kV HVDC. In selecting an appropriate preliminary HVDC voltage rating for Concept 1, it was decided to select a DC line current rating similar to the Pacific Intertie project and a standard HVDC voltage rating already in use in other HVDC overhead transmission line projects. By choosing a voltage rating of ±600kV HVDC (i.e., the voltage rating for the Itaipu project in Brazil), Concept 1 benefits from availability of existing and proven designs for overhead transmission line equipment and HVDC converter station components, including insulators, disconnect switches, transducers, etc. Also, with a ±600kV HVDC voltage rating, the DC line current rating for Concept 1 (i.e., 3,333 Amperes) will be within the available ampacity ratings for modern HVDC converter stations.

PJM provided minimum single-contingency (N-1) short-circuit capacity data of 36,300 MVA (27.4 kA at 765kV) and 15,850 MVA (18.3 kA at 500kV) for the Amos and Kemptown substations, respectively. Based on that data, LCC-technology was selected for the HVDC converter stations at Amos and Kemptown for Concept 1. In addition, conceptual designs and preliminary layout drawings were prepared for the HVDC converter stations at Amos and Kemptown based on installation of two twelve-pulse 2,000 MW LCC units per HVDC converter station, with each LCC unit connected pole-to-neutral. This approach is consistent with the design of other modern high-capacity HVDC overhead transmission line projects. Figure 3.7 shows the configuration of a typical HVDC overhead transmission line project with two 600kV HVDC, 2,000 MW, LCC units per HVDC converter station.

As illustrated in Figure 3.7, the proposed conceptual design for Concept 1 between Amos and Kemptown is a Bipolar ±600kV HVDC overhead transmission line (HVDC Overhead Line), in that each pole can be operated without the opposing pole. One HVDC converter station unit will provide the positive pole and the other will provide the negative pole with a common neutral. Each of the
poles will create a separate circuit with the positive (+) pole or negative (-) pole
conductor and a shared metallic return conductor on the HVDC Overhead Line. Since it appears unlikely that the PATH Project will be able to obtain a permit for
temporary injection of the full DC line current into a ground electrode station in
connection with a fault on one pole, it was decided to include a metallic-return
conductor in the conceptual design of the HVDC Overhead Line for Concept 1 to
maintain the system reliability benefits of the Bipolar design of the HVDC
converter stations.

Based on review and consultation with PJM, it was determined that a 4,000 MW
HVDC converter station rating will not be needed at Welton Spring since a loss of
the entire 4,000 MW transmission capacity between Amos and Kemptown will be
a Category C event under NERC TPL-003. Therefore, a preliminary 2,000 MW
HVDC converter station rating was selected for Welton Spring for Concept 1.

PJM provided minimum single-contingency (N-1) short-circuit capacity data of
6,400 MVA (7.4 kA at 500kV) for the Welton Spring substation and, based on
that data, LCC-technology was selected also for the HVDC converter station at
Welton Spring. Conceptual designs and preliminary layout drawings were
prepared for the HVDC converter station at Welton Spring based on installation
of two twelve-pulse 1,000 MW LCC units, with each LCC unit connected pole-to-
neutral.

Figure 3.8 shows the three-terminal HVDC transmission system configuration
selected for Concept 1. Note that commercial designs, control systems and
switching devices for multi-terminal HVDC transmission systems have been
available since the 1980s and that operation of such HVDC transmission
systems has been proven in several existing HVDC transmission line projects,
including the Pacific Intertie HVDC expansion project between Oregon and
southern California (commissioned in the late 1980s) and the 2,000 MW Quebec-
New England Phase II HVDC project (third terminal was commissioned in the
early 1990s).
Additional AC grid analysis is still required before PJM can conclusively determine that the proposed 2,000 MW HVDC converter station rating at Welton Spring for Concept 1 will provide similar AC grid reliability performance as the Base Design alternative proposed in the current PJM transmission expansion plan. If such additional PJM analysis would conclude that a significantly higher HVDC converter station rating is required at Welton Spring, the relatively low single-contingency short-circuit capacity at that location may necessitate either additional reinforcement of the AC grid or the use of VSC technology for the Welton Spring HVDC converter station.

3.3.2 AC Overhead Line from Amos to Welton Spring and HVDC Underground Line from Welton Spring to Kemptown – Concept 2
In this Study, the Concept 2 design option for the PATH Project includes overhead construction for the transmission line segment from Amos to Welton Spring and all underground construction for the transmission line segment from Welton Spring to Kemptown.
Concept 2 is based on the use of XLPE cables specifically designed for use in an
HVDC underground transmission line. See Section 4.1 of this Study for a
discussion of alternate cable types and their feasibility for this installation.

Typically, the most economical way to construct an HVDC underground
transmission line is to use a pair of identical cables with the same conductor size
and insulation rating to ground. With a pair of XLPE cables rated for 400kV
HVDC to ground (i.e., the highest HVDC voltage rating that is expected to be
commercially available within the planned construction period for the PATH
Project), each circuit will have a rating of 800kV (±400kV). For a 4,000 MW
HVDC underground transmission line capacity from Welton Spring to Kemptown,
it will be necessary to construct three parallel circuits each rated for 800kV
(±400kV) HVDC, 1,333 MW (HVDC Underground Line).

To match the technical characteristics and ratings of the HVDC Underground
Line, Concept 2 includes construction of three Symmetrical 800kV (±400kV)
HVDC VSC converter stations at Kemptown also rated 1,333 MW each. One
dedicated VSC converter station per circuit appears to be the most practical,
economical and reliable way to match the VSC converter station capacity to the
characteristics of the HVDC Underground Line, and is consistent with designs
used in existing VSC-based HVDC underground and submarine cable
transmission systems.

Only AC Overhead Line construction was considered between Amos and Welton
Spring in the conceptual design and cost estimates for Concept 2. For the Amos
to Welton Spring line segment (overhead transmission construction for PATH
Concept 2), any HVDC overhead transmission line design needs to match the
HVDC Underground Line design for the segment between Welton Spring and
Kemptown. That is, an HVDC overhead transmission line design needs to
include three parallel circuits each rated for 1,333 MW, Symmetrical 800kV
(±400kV) HVDC. Since such an HVDC overhead transmission line design will
likely require as much, if not more, right-of-way width and height as the Base
Design alternative proposed in the current PJM transmission expansion plan, it
appears to make little sense to consider more expensive HVDC converter station
construction at Amos for Concept 2.

To match the technical characteristics and ratings of the HVDC Underground
Line and VSC converter stations at Kemptown, Concept 2 includes construction
of three Symmetrical 800kV (±400kV) HVDC VSC converter stations at Welton
Spring rated at 1,333 MW each. Figure 3.9 provides a system overview of the
conceptual design configuration for Concept 2.
3.4 System Operation and Performance

Like other types of control devices, such as generator excitation system controls, static VAr systems, wind turbine controls, etc., HVDC converter station controls could potentially interact with AC grid interconnected devices. Review of such potential interaction is typically part of the detailed engineering and design of new HVDC transmission systems. Algorithms in modern computer based HVDC converter station controls are reliable and robust and incorporate decades of continuous development and operating experience. If potential interaction is identified or experienced during design or operation, modern computer based HVDC converter station controls can easily be adapted and adjusted to eliminate potential for undesired interaction.

As reported in EPRI EL-2708, Research Project 1425-1, a new HVDC transmission system can potentially cause adverse torsional interaction with turbine-generators located electrically close to the HVDC converter stations. Review of potential risk for such sub synchronous torsional interaction (“SSTI”) is always part of detailed engineering and design of HVDC transmission systems for generators located electrically close to the HVDC converter stations.

Per industry practice, SSTI review is typically performed in two steps. First, a SSTI screening study analyzes the Unit Interaction Factor (UIF) (as defined in EPRI EL-2708, Research Project RP1425-1, Final Report, 1982) for critical network conditions where the HVDC transmission system could potentially interact with a torsional mode frequency of a nearby turbine-generator. If the initial SSTI screening study identifies one or several such critical conditions,
detailed torsional mode frequency data is collected for the affected turbine-generator(s). The HVDC converter station control systems are then adjusted such that there will be no potential for harmful interaction with identified critical torsional mode frequencies.

Both LCC- and VSC-based HVDC converter stations are typically designed for unattended operation. Periodic maintenance or inspections are required but, because of built-in redundancy and duplication of essential components and subsystems, most of these tasks can be performed without an outage or impacts to the transmission capacity. Recommended maintenance intervals that require an outage are typically biennial with most of the work being performed on one pole or circuit at a time while the other pole or circuit remains in operation at its full transmission capacity.

Calculated and guaranteed availability for both forced and scheduled outages for HVDC converter stations typically exceed 98%. The level of redundancy provided in modern HVDC converter station design and stocking of spare parts at site insures high system availability with unavailability due to forced outages typically less than 0.5%.

Actual performance data for HVDC transmission systems worldwide is reported to and published by CIGRE under its “Protocol for Reporting the Operational Performance of HVDC Transmission Systems” published by CIGRE 14-97 (WG 04). For illustration, reported performance data from the Cross Sound HVDC cable project between Connecticut and Long Island is listed below for the period of July 1, 2005 and June 30, 2006:

Cross Sound Cable Operation and Maintenance History

- **Forced Outages  July 1, 2005 – June 30, 2006:** Total of 32.19 hours with an Forced Energy Unavailability of 0.37%
  - Auxiliary Power – 1.02 hrs
  - AC Circuit Breaker – 2.18 hrs
  - Maintenance Error – 9.85 hrs
  - Protection Setting – 19.14 hrs

- **Scheduled Outages  July 1, 2005 – June 30, 2006:** Total of 113.19 hours with a Scheduled Energy Unavailability of 1.29%
  - Auxiliary Power Upgrade – 31.14 hrs
  - IGBT Exchange – 14.3 hrs
  - Annual Scheduled Maintenance – 64.92 hrs
  - Control and Protection Revision = 2.83 hrs

- **Energy Availability  July 1, 2005 – June 30, 2006:** 98.3%
3.5 Maintenance Considerations
Modern LCC and VSC-based HVDC converter stations are designed to minimize maintenance. Due to built-in redundancy and duplication of essential components and subsystems, most maintenance tasks can be performed without an outage or capacity impacts. Recommended maintenance intervals that require an outage are typically biennial with most of the work being performed on one circuit at a time while the other circuits remain in operation at full transmission capacity. For example, during a maintenance outage of one circuit in Concept 1, 2,000 MW of transmission capacity would stay in service. Similarly, with a maintenance outage of one circuit in Concept 2, 2,666 MW of transmission capacity would stay in service.

The average work per year for scheduled maintenance that requires an outage is typically in the range of less than 200 man-hours. Depending on the Owner’s maintenance philosophy as to the size of crews and length of working days, annual maintenance can typically be accomplished within three days.

HVDC converter stations are normally designed for remote operation and there is no requirement for having personnel on site. Even though HVDC transmission systems generally have the capability to be operated from either HVDC converter station, this is for back-up and not a typical operating mode. (HVDC transmission systems are normally operated remotely from a central control or dispatch center.)

3.6 Permitting Considerations
There are no clear permitting advantages for either HVDC converter technology.

Compared to an AC substation, both HVDC converter station types have an increased footprint, which may trigger some additional permitting requirements.

3.7 Future Expansion
Future expansion of HVDC converter station capacity is possible through many different means depending on capacity requirements, including by upgrading converter unit and converter transformer cooling systems for small capacity increments and by addition of series and/or parallel connected converter units for major capacity expansion. For example, the original HVDC converter station capacity rating for the Pacific Intertie HVDC Project between Oregon and southern California was 1600MW, ±400kV. The project HVDC converter station capacity rating was expanded in the early 1980s to 2000MW, ±500kV, by adding a new 100kV series connected converter unit in each pole at the HVDC converter stations in Oregon and California. In the late 1980s, the HVDC converter station capacity was expanded to 3100 MW by adding a new parallel 550MW, 500kV, converter unit in each pole. New parallel HVDC converter stations can also be
located at new locations along the transmission line if requirements for additional tapping of power would develop in the future.

3.8 Estimated Cost

The following Cost Estimates apply for the LCC-based HVDC converter stations for Concept 1:

- Bipolar ±600kV HVDC, 4000 MW (2x2000 MW) HVDC converter station at Amos -- $300 million
- Bipolar ±600kV HVDC, 2000 MW (2x1000 MW) HVDC converter station at Welton Spring -- $238 million
- Overhead Tap DC Switchyard near Welton Spring -- $8 Million
- Bipolar ±600kV HVDC, 4000 MW (2x2000 MW) HVDC converter station at Kemptown -- $300 million

The following Cost Estimates apply for the VSC converter stations for Concept 2:

- Three VSC converter stations rated Symmetrical 800kV (±400kV) HVDC, 1333 MW each at Welton Spring -- $696 million
- Three VSC converters stations rated Symmetrical 800kV (±400kV) HVDC, 1333 MW each at Kemptown -- $696 million

The above Cost Estimates include design, equipment supply, site development, installation, site supervision and commissioning of all equipment, subsystems and systems along with balance of plant costs. See Appendix G for a summary of the Cost Estimates.

The above Cost Estimates are based on June 2009 commodity prices and cost of labor. Also, the price estimates for the HVDC converter station materials are based on a currency exchange rate of 7.5 Swedish Kronor per US dollar.

Note: It is hereby understood that neither the Cost Estimate data, its associated commercial terms nor any past or future action, course of conduct or failure to act by either ABB, Black & Veatch or PJM regarding the PATH project will give rise to or serve as a basis for any obligation or other liability on the part of the parties or any of their affiliates. Neither party shall be obligated to enter into any further agreement with another party. Any commitment, agreement or binding obligation with respect to the PATH project would only arise and would be subject to, among other things, the negotiation, the due execution and delivery by the parties of the Definitive Agreement regarding the Path Project.
4.0 HVDC Underground Cable System

For the Welton Spring to Kemptown segment of the proposed PATH Project, HVDC underground transmission is being considered as an alternative to AC or HVDC transmission using traditional overhead construction.

4.1 Technology Comparison

Most of the HVDC underground transmission lines installed around the world are part of submarine cable projects. There are a few examples where the HVDC underground cables are not part of a longer submarine cable system, including a 112 mile long HVDC underground transmission line in Australia. This section contains short descriptions of the feasible HVDC underground cable types along with a short discussion of benefits and drawbacks in regards to the PATH Project.

4.1.1 High Pressure Fluid Filled (HPFF)

HPFF cables are utilized in the majority of existing underground transmission lines in North America; however, HPFF cables are used less often for new underground transmission line installations due to the maintenance required and increased environmental concerns.

HPFF cables are insulated with Kraft paper or paper/polypropylene/paper (PPP) tapes impregnated with high-viscosity synthetic oil. D-section skid wires which can be stainless steel, brass or zinc, are wound helically around the cable to reduce friction between the cables and the pipe wall. The cables are drawn into a common steel pipe which is coated with an insulating material and provided with cathodic protection. The space between the cables and the steel pipe is filled with a low-viscosity synthetic fluid (alkyl benzene or polybutene) which is pressurized to a minimum of 200 psi to improve electric strength of the cable insulation. The use of PPP insulation in place of Kraft paper allows a reduced cable insulation wall and steel pipe diameter resulting in improved power transmission capacity.

There are no commercial HVDC underground transmission line installations using HPFF cable, although a 600kV HVDC design has passed EPRI Waltz Mill acceptance tests.

4.1.2 Self Contained Fluid Filled (SCFF)

The construction of SCFF cables is similar to that of an HPFF cable in that both employ a laminar dielectric, which can be either Kraft paper or PPP tapes, impregnated with a dielectric fluid which is maintained under pressure to improve its electrical strength. There are, however, several important differences as follows:
• The conductor has a central duct to allow the dielectric fluid to reach the taped insulation. During the expansions and contractions which accompany load variations, the fluid flows along the conductor duct to and from special fluid reservoirs via feed joints at intermediate points along the route; or, for very long lines, to large pumping plants via the terminations at one or both ends of the line.

• The insulated conductor is contained in a metallic sheath which can either be corrugated aluminum or lead reinforced with metal tapes to resist the internal fluid pressure. The fact that this sheath is an integral part of the cable construction rather than a separate pipe is the origin of the term “self-contained”.

• In order to protect against corrosion, the metal sheath is provided with a high grade extruded polymeric over-sheath (jacket). The most frequently used jacket is a medium or high density polyethylene with a 2% addition of carbon black as a protection against UV.

SCFF cables have been used for HVDC underground transmission lines since the 1980’s and are typically only used for relative short lines with only a few projects more than 10 km long.

SCFF cable for the PATH Project may cause environmental concerns due to the required dielectric fluid and pressurization equipment. Intermediate pressurization reservoirs along the route will be required along with the associated communications and alarm equipment to monitor the dielectric fluid level.

4.1.3 Mass Impregnated (MI)

The majority of HVDC submarine transmission line installations are constructed using mass impregnated (MI) cable. The MI or “solid type” paper insulated cable is so called because the paper tape insulation is impregnated with a very high viscosity dielectric fluid which does not drain at moderate operating temperatures thus avoiding the need for fluid pressurization. The MI cable resembles SCFF cable in cross section, except that there is no fluid channel in the conductor.

The first MI cable used for HVDC transmission was the 62.1 mile long, 100kV HVDC, 20 MW submarine transmission line between the Swedish Mainland and the offshore Island of Gotland and was installed in 1956. Since then, MI cable has seen extensive HVDC submarine transmission line application with approximately 1875 circuit miles in service worldwide at the present time. More than 30% of the installed MI cable is in the 400kV to 500kV HVDC voltage range with a further 1400 circuit miles planned to be in service by 2010. The majority of MI cable used for land based underground transmission is an extension of a submarine transmission line installation. For example, the
Neptune 500kV HVDC transmission line between Sayreville, NJ and Long Island, NY has approximately 50 circuit miles of submarine MI cable underwater in New York Harbor and 14 circuit miles of underground MI cable installed in duct banks along the Wantagh State Parkway on Long Island.

Progress in the development of MI cables for HVDC transmission applications is summarized in the following Table:

<table>
<thead>
<tr>
<th>Voltage (kV)</th>
<th>Project</th>
<th>Length (circuit miles)</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>Gotland Island - Sweden</td>
<td>62.1</td>
<td>1956</td>
</tr>
<tr>
<td>200</td>
<td>Sardinia - Corsica - Italy</td>
<td>73.3</td>
<td>1965</td>
</tr>
<tr>
<td>300</td>
<td>Vancouver Island - Canada</td>
<td>16.8</td>
<td>1969</td>
</tr>
<tr>
<td>400</td>
<td>Sweden - Finland</td>
<td>124.3</td>
<td>1989</td>
</tr>
<tr>
<td>450</td>
<td>Sweden - Germany</td>
<td>155.3</td>
<td>1994</td>
</tr>
<tr>
<td>500</td>
<td>New Jersey - Long Island</td>
<td>65.3</td>
<td>2007</td>
</tr>
</tbody>
</table>

MI cables are the most common cables for HVDC submarine transmission line installations. Once installed, MI cables do not require significant maintenance, providing for lower operating costs.

MI cable is also especially suited for submarine transmission line applications because a cable laying ship can be used to transport extremely long lengths of MI cable as a single segment which minimizes the number of field splices required. However, the PATH Project is a land based installation and will require the MI cable to be transported by truck, thus limiting the MI cable segment lengths to approximately 2000' long. Each MI cable segment will require an MI cable field splice which is labor intensive and sensitive to quality control.

4.1.4 Cross-Linked Polyethylene (XLPE)
Extruded dielectric cables using XLPE insulation have become the most common cable type for new EHV installations. This is mostly due to XLPE cables requiring very little maintenance over their lifetime. Extruded dielectric cables for HVDC transmission applications are a relatively recent development. The first North American installation was in 2002, the Cross-Sound Cable Link in Long Island Sound. The construction of XLPE cables for HVDC transmission required the development of modified XLPE formulations that resist the build up and migration of space charges. Several manufacturers are developing XLPE cable systems for HVDC transmission, with three manufacturers having commercially available designs.

XLPE cables have the same basic components as the other cable types. At the center of the cable is a stranded conductor made of copper or aluminum. The insulation system is installed over the conductor. The insulation material and the semi-conducting conductor and insulation shields are extruded and chemically
cross linked during the extrusion process. All three layers are extruded simultaneously in a so-called triple extrusion head to ensure continuous bonding and clean interfaces. The thickness of the insulation depends on the allowable electrical stresses in the insulation system. Increasing the thickness of the insulating layer will decrease the electrical stresses on the insulating materials. Due to the proprietary nature of the insulating materials used in XLPE cables for HVDC transmission, there are no standard thicknesses. Each manufacturer is developing designs based on their particular insulation formulation.

XLPE materials are sensitive to the presence of moisture during operation. To protect the insulation from moisture, a continuous metallic sheath surrounds the insulation core. Several different types of metallic sheaths are used including corrugated aluminum, corrugated copper, laminated aluminum or copper foil, and extruded lead alloy.

The sheath is protected from corrosion and abrasion by an extruded polymeric cable jacket. The jacket is typically constructed of medium or high density polyethylene.

An example of an XLPE cable rated for 400kV HVDC is shown in Figure 4.3, below:
Figure 4.3: An example of XLPE cable rated for 400kV HVDC.

- **Conductor**
  - Type / material: profiled strands / copper
  - Cross-section: 2,000 mm²
  - Diameter: 2 inches (52 mm)

- **Conductor shield**
  - Material: semi-conductive polymer
  - Thickness: 59 mils (1.5 mm)

- **Insulation**
  - Material: cross-linked DC polymer
  - Thickness: 866 mils (22 mm)

- **Insulation shield**
  - Material: semi-conductive polymer
  - Thickness: 47 mils (1.2 mm)

- **Longitudinal water barrier**
  - Material: semi-conducting swellable tape
  - Thickness: 24 mils (0.6 mm)

- **Metallic screen**
  - Type / material: round wires / Cu
  - Thickness: 43 mils (1.1 mm)

- **Longitudinal water barrier**
  - Material: semi-conducting swellable tape
  - Thickness: 24 mils (0.6 mm)

- **Radial water barrier**
  - Type / material: longitudinal applied foil / Al
  - Thickness: 7.9 mils (0.2 mm)

- **Outer jacket**
  - Material: high-density polyethylene
  - Thickness: 196 mils (5 mm)

- **Complete cable**
  - Diameter: 4.7 inches (120 mm)
  - Weight in air: 24 lbs./ft. (37 kg/m)

*Note: All data provided shall be considered nominal*
The use of XLPE cables for HVDC transmission has been delayed compared to AC transmission due to complications with insulation design caused by space charge accumulation which causes a significant reduction in the electric strength at the operating temperature, particularly when the polarity is reversed to reverse the direction of power flow. Progress in the development of modified XLPE using special “functional groups” has apparently been successful in solving the space charge problem, and as a result, the first modified submarine transmission line using XLPE cable was installed in Long Island Sound in 2002. This was followed in 2006 by a similar submarine transmission line project between Finland and Estonia, a distance of some 46.6 circuit miles. Both submarine transmission lines are in operation at ±150kV HVDC, the highest operating voltage presently in service. The year 2009 should see the completion of the 53 circuit mile long Transbay submarine transmission line project between Pittsburg and San Francisco, CA, using XLPE cable rated at ± 200kV HVDC. One 28 circuit mile submarine transmission line project using XLPE cable rated at ±250kV is now under contract and the XLPE cables are expected to be in operation in 2011.

Modified XLPE HVDC technology has also been used for land based underground transmission line applications which include the ±150kV HVDC, 112 circuit mile long Murraylink project in Australia which was installed in 2000.

Several manufacturers have qualified or are in the process of qualifying their XLPE cable systems for commercial use at the ±300kV HVDC level. These XLPE cable systems have passed high voltage type testing and prequalification testing, but have not yet been installed for commercial operation. There currently are no XLPE cable systems qualified at the ±400kV HVDC level, but three cable manufacturers are currently developing their cable systems for operation at ±400kV HVDC or higher. Concept 2 as proposed in this Study will require the use of XLPE cable rated for operation at Symmetrical 800kV (±400kV) HVDC. There is some risk, that this new technology may not be available to support the in-service date for the PATH Project. ABB expects to have the first ±400kV HVDC rated XLPE cable system qualified for commercial use in 2011 which will support the PATH Project in-service date. Other manufacturers expect to have their XLPE cable systems qualified by 2014.

The lack of commercial installations of XLPE cable rated for operation at the ±400kV HVDC voltage level means the PATH Project will likely be a first of a kind installation. First of a kind installations have elevated risks compared to typical installations; however, in the case of HVDC XLPE cables, the risk increase should be minor. HVDC XLPE cables are similar in construction to AC XLPE cables, which are qualified at higher voltage levels. Also, the experience record to date for HVDC XLPE cables has been good with no known failures to date due to manufacturing defects.
XLPE cable has many of the same benefits as MI cable. Once installed, the cable system needs very little maintenance, mostly limited to annual or semi-annual inspections of the cable terminations.

Like MI cable, XLPE cable is also limited to approximately 2000 feet per segment due to transportation. However, it is easier to assure the quality of splicing workmanship for an XLPE cable system, since the splice can be pre-molded and tested in the factory.

4.1.5 Gas Insulated Line (GIL)
GIL systems are typically used for short connections where high power transfer is required such as substation ties.

The construction of a typical GIL consists of an aluminum tube conductor supported concentrically within an aluminum enclosure by epoxy cast insulators; a post design is used within a longitudinal section with conical insulators as a gas barrier at the section ends. In most existing systems, the gas insulation is SF$_6$ gas at pressures of 30-60 psi. SF$_6$ is a greenhouse gas with leak limits imposed by the Kyoto Protocol. For this and other more technical reasons modern systems use a 20% / 80% SF$_6$ / nitrogen mixture at a higher pressure in the region of 105 psi.

As of the time of this Study, there are no HVDC transmission lines using GIL.

4.1.6 Cable Type Recommendation
HPFF cable and GIL have not been used for HVDC transmission lines and do not provide benefits significant enough for further consideration in this Study. SCFF cable will face significant resistance for environmental reasons. MI cable and XLPE cable are both technically feasible for HVDC transmission lines, with similar benefits and drawbacks. XLPE cable will be used for comparison purposes for the rest of this Study, but MI cable remains a technically feasible alternative.

4.2 Conceptual Design
The installation for the cable is designed to provide mechanical protection for the cable, as well as dissipate the heat generated by electrical losses in the cable. The easier an installation can dissipate heat, the more load an individual cable can carry. The following installation methods were evaluated for various portions of the route. See Appendix D of this Study for typical underground installation cross-sections.

4.2.1 Direct Buried
Direct burial is the lowest cost method of installing underground transmission lines. Construction begins by opening a trench from above grade. Then a thin layer of thermal sand or other bedding material is laid on the bottom of the
trench. The cables are laid on top of the bedding material, and then backfilled with more bedding material. The bedding material is designed to dissipate heat from the cables.

Above the bedding material, a concrete slab is typically installed to provide physical protection. The slab can be poured in place or pre-cast and delivered to the site. Above the concrete slab the trench is backfilled, with native soil or a corrective backfill. Corrective backfill will be required to improve the heat dissipation characteristics of the installation if the native soil does not provide good thermal characteristics. The top of the protective slab is typically a minimum of 36 inches below grade to minimize the chances of a dig-in. The top 12 to 18 inches of backfill is installed to match the surrounding environment.

For the direct buried installation, each pair of cables will need to be installed in a separate trench, with approximately 33 feet of separation between trenches to minimize the mutual heating and facilitate heat dissipation. The individual trenches are approximately two feet wide. The total installation will be approximately 68 feet wide. Additional space will be required on either side of the total installation for future maintenance and repair work, for a total permanent right-of-way width of approximately 90 feet. During construction, additional right-of-way space will be required for handling and stockpiling materials, requiring a temporary construction right-of-way width of approximately 110 feet wide.

The splices for a direct buried installation are assembled in pits, and then covered with concrete boxes only slightly larger than the splice. The splice enclosures are then filled with thermal sand and buried. There is no access to inspect or repair the splices without excavating and removing the enclosures.

4.2.2 Horizontal Directional Drill (HDD)
When faced with obstacles, such as open water or highways, where trenched installations are not acceptable, the cables can be installed by trenchless technologies such as the horizontal directional drilling (HDD) method.

HDD installation is accomplished using a large hydraulic drill rig. The rig requires a minimum of 50 foot x 100 foot of dry, flat area on each side of the rig for set up. The first step in the installation is to drill a pilot hole using a guided drill bit. Next the pilot hole is widened by pulling increasingly larger reamers through the bore hole. When the bore hole is wide enough, a bundle of conduits is pulled into the bore hole.

For this installation each pair of cables will require separate bundles of conduits with a minimum of 33’ separation between bundles. Each bundle will consist of three (3) 10-inch and one (1) 5-inch plastic conduits. The heavier wall thickness and more significant pressures on the conduits requires a larger bore hole nominal diameter than for a comparable duct bank installation. The conduits can...
be made of high density polyethylene (HDPE) or a heat fusible polyvinyl chloride (FPVC). These materials can be joined into a single long conduit by heating the ends of shorter conduits and pressing them together. This allows for longer drill lengths.

While the HDD rig can install HDPE conduit up to 3000 feet and FPVC conduit in excess of 6000 feet, only approximately 2000 feet of cable can be shipped on a standard reel, limiting how far a single installation can run. Oversized reels can be made, but special consideration will have to be given to transportation requirements for oversized loads weighing more than 60,000 pounds.

4.2.3 Eagle River Gorge/ Trough
Approximately 2.3 miles east of the proposed Welton Spring substation site the route crosses the Eagle River Gorge. This gorge represents an elevation change of several hundred feet and a horizontal span of approximately 5000 feet. It is not possible to cross at this location using a cable installation; however a potential alternate route is located approximately 1 mile south of the currently proposed crossing. This alternate location could be crossed using an HDD. The reroute will add approximately 0.9 miles to the overall route length.

4.2.4 Lily Pons Water Garden
Near Lily Pons, Maryland the route crosses an area called the Lily Pons Water Garden. The Lily Pons Water Garden is a privately owned fishery and water gardening nursery established in 1917. In aerial imagery, the area appears to be artificial wetlands and will be treated as wetlands for the purpose of this Study.

Due to the amount of disturbance trenching causes in wetlands, it is typical to cross under them using an HDD or route around them. The HDD path there will be too long, so an alternate route along Park Mills Rd. has been used for the Cost Estimate. This alternate route will add approximately 0.5 miles to the route length, along with increased impact to the public, as the road will need to be reduced to a single lane during construction.

4.3 Maintenance and Operation Considerations
Underground cable systems are considered to be reliable, require minimal maintenance after installation, and have minor operating differences when compared with overhead transmission.

4.3.1 Reliability
Unlike overhead transmission, underground cable systems are not exposed to environmental fault hazards; therefore, non-scheduled outages are much more common for overhead transmission when compared to underground transmission. The most common type of overhead transmission fault is insulation failure caused by lightning strikes or environmental contamination. If a fault does occur, for either overhead and underground transmission, modern
protective relaying systems can detect the fault point to within a few spans. The advantage with overhead transmission is that the actual fault point is easily detected by visual inspection of the insulation which typically shows burning at the fault point; however, for underground transmission, the faulted circuit will have to be disconnected and a separate test set (burner/thumper) will have to be used to locate the actual fault point. Overhead transmission insulation faults are also relatively easy to repair. The main disadvantage with overhead transmission, although very rare, is a catastrophic failure of the entire line segment due to an environmental condition, e.g. extreme icing, that exceeds the design conditions.

The main advantage for underground cable systems is that they are inherently immune to insulation failure due to lightning strikes or environmental contamination. Only the terminators, which are a small part of the entire system, are exposed to the environment. Typically, surge arresters are installed close to the terminators to mitigate lightning or switching surges from damaging the insulation.

Due to the relatively smaller quantities of underground cable systems installed, it is difficult to get accurate reliability statistics for comparison purposes; however, it is clear that the most common cause for failure is a dig-in or external damage due to a third party. Faults in an overhead transmission line are much more common than faults in a cable system; however repairing faults in a cable system requires weeks compared to days for an overhead transmission system. Reliability statistics, such as total lifetime duration out-of-service tend to be less for underground cable systems, but the longer duration of non-scheduled outages may have more significant impacts to power system operation.

### 4.3.2 Splices and Terminations

Failures in a cable system that are not caused by external damage (dig-in) typically occur in splices or terminations. The cable itself is manufactured and tested to industry standards, leaving the field installation of splices and terminations as the most likely failure point. While failures are rare, the more splices and terminations included in the cable system, the higher the chances for a failure are. Depending on the voltage class, splices and terminators may not be a stock item and will take several months to procure. Utility companies plan ahead for this and stock spare splices and terminators which reduce the overall outage time if a fault does occur.

### 4.3.3 Operation

The differences in operation between overhead and underground transmission lines are relatively minor. The biggest fundamental difference in operating philosophy between overhead and underground transmission is the ability of a cable system to spread thermal losses out over the course of a day, allowing the cable system to be sized based on the average daily load, compared to the peak
load, making cable systems particularly well suited to peaking loads. Cable system ratings are typically presented as peak load for a given daily load factor (daily average load / peak daily load).

Recently cable systems have included distributed temperature monitoring systems (DTS) based on optical fibers integral to the power cable or in separate fiber-optic cables along side the power cables to monitor the cable temperature in real time which provides valuable information to assist the operator in determining the loading capability. Costs for a DTS system have not been included in the Cost Estimate but would typically increase cable system costs by less than 3%.

### 4.3.4 HDD

The installation of portions of an underground transmission line by HDD presents some additional considerations. As the HDD installed portions of the cable system are typically not accessible, any damage to the cable system in these areas will require significantly more time to repair than direct buried sections of the transmission line. Spare conduits are typically installed in the HDD to allow a replacement cable section to be installed with the faulted cable abandoned in place.

In addition, HDD installations are deeper, requiring larger cable conductors or wider right of way to achieve the same loading capacity. The HDD is typically the “thermal choke point” which limits the capacity of an underground transmission line.

### 4.3.5 Concrete Encased Duct Bank

For the purpose of this Study, the installation was estimated using direct buried cable for most of the route. Direct buried installations are particularly well suited to installations in existing transmission right-of-ways or unimproved areas; however, due to the circuit separation required and the overall right-of-way width, direct buried installations are not as particularly well suited for urban or congested areas. In urban or congested environments, underground transmission lines are typically installed in concrete encased duct banks for the entire route.

Concrete encased duct bank installations require less than two thirds the right-of-way of direct buried installations, provide additional protection from dig-ins, and decrease the time required to repair a cable system. The PATH Project will require the cable circuits to be installed in three separate duct banks to meet the circuit loading requirements.

Concrete encased duct banks will also increase the cost of the installation by approximately 15%.
4.4 Estimated Cost
The Cost Estimates are based on a 100 mile long route using XLPE cables. The Cost Estimate includes allowances for reroutes related to the Eagle River Gorge and Lily Pons Water Garden, adding 1.4 miles to the overall route. See Appendix H for the Underground Cost Estimate Summaries.

4.4.1 Basis and Accuracy of Estimates
The Cost Estimates are made on the basis of public information. Detailed analysis of the underground transmission line design, soil conditions, and geographic conditions have not been conducted.

The individual cost items have been estimated using previous construction data from the East Coast and the Mid-Atlantic Region. The XLPE cable and accessories Cost Estimates are based on information from ABB.

These Cost Estimates have an approximate order of accuracy of ±30%. More detailed estimates will require detailed analysis of the existing conditions and design challenges.

4.4.2 Permitting, Right-of-Way Acquisition, and Mitigation
It is difficult to estimate costs for permitting, right-of-way acquisition, and environmental mitigation due to the large variation in cost by geographic area and local conditions. The relative difference in costs between Concept 1 and Concept 2 will be minor and will be approximately proportional with the difference in right-of-way required.

4.4.3 Major Assumptions
The Cost Estimates are based on the following major assumptions. For a complete listing of assumptions see Appendix H.

- The estimate does not include costs related to right of way acquisition.
- The estimate does not include costs related to habitat remediation.
- The estimate does not take into account work restrictions due to wildlife or environmental conditions.
- The estimate does not include permitting costs.
- The estimate does not include overhead or internal costs for the utility.

4.4.4 Total Route Cost Estimate
The Cost Estimate for installing the entire length of the route from the proposed Welton Spring substation to Kemptown is estimated as $884 Million. These
costs include the complete engineering, procurement, construction and construction management costs in accordance with the assumptions listed in above and in Appendix H.

The total route is assumed to be 100 miles long as indicated in Appendix C of this Study with an additional 1.4 mile allowance for reroutes required due to the terrain.

This route will require approximately 268 pairs of cable splices for each circuit, for a total of 1608 single cable splices. Splice quantity is an approximate number estimated on overall route length and expected shipping length. Splice quantity may change with specific installation requirements and cable designs. The terrain types for the route are based on overhead imagery and limited photographs. It is assumed the route includes approximately 28.3 miles of agricultural, 56.5 miles of cleared existing transmission corridor, 2.0 miles of lightly forested, and 4.6 miles of heavy forested, and 10.0 miles of roadway and waterway crossings by horizontal directional drill.
5.0 HVDC Overhead Transmission System
The conceptual design of the HVDC overhead transmission system was
developed to be consistent with many of the aspects of the Base Design. Much
of the basis for the HVDC overhead transmission system was taken from project
information provided on the PATH Project web page (www.pathtransmission.com) and from the Joint Application for Certificates of
Public Convenience and Necessity (CPCN application) filed by the PATH Project
before the Public Service Commission of West Virginia. However, the Cost
Estimates in this Study are conceptual in nature and not intended to capture all of
the design features of the PATH Project, most of which have not been
determined at this time.

5.1 Welton Spring to Kemptown
A double circuit Bipolar ±600kV HVDC overhead transmission line (HVDC
Overhead Line) was evaluated as an alternative for the Welton Spring to
Kemptown segment of the Path Project. The route between Welton Spring and
Kemptown used for this Study is approximately 100 miles long and is shown on
the Estimated Route for Transmission Map included in Appendix C.

5.1.1 Conceptual Design
The HVDC Overhead Line will utilize a combination of lattice steel towers and
single shaft tubular steel structures. All of the structures will be self supporting.
The predominate structure type will be lattice steel towers with the tubular
structures being utilized only in agricultural areas with cultivated crops and where
138kV AC transmission underbuild is needed. Other structure types may be
needed to deal with site specific design requirements but those have not been
evaluated as part of the conceptual design. The tubular tangent structures will
be single shaft structures with the two (+) and (-) pole conductors supported on
horizontal davit arms. The angle and dead end tubular structures will consist of
3-shaft structures. The quantity of angle and dead end structures was estimated
from the PATH Project route maps. The average span length is estimated at
1350 feet which is consistent with the average span length in the PATH Project
CPCN application to the West Virginia PSC.

Each pole conductor will consist of a bundle of three (3) sub-conductors arranged
in a triangular pattern. The sub-conductors are 1272 kcmil 45/7 ACSR "Bittern"
conductors. The pole-to-pole spacing is approximately 50 feet. The HVDC
Overhead Line will also have a metallic return conductor which will be equivalent
in size to the pole conductors and will be capable of carrying 2,000 MW in the
event that one of the pole conductors is inoperable. However, the metallic return
conductor will be insulated for 35kV phase-to-ground, not ± 600kV HVDC. The
HVDC Overhead Line will also have two (2) 1 inch diameter optical ground wires
(OPGW) to be consistent with the Base Design.

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Average structure heights were determined to maintain 35 feet of ground clearance with a conductor temperature of 212°F and 50 feet of ground clearance with a conductor temperature of 120°F at the average span length of 1350 feet. A detailed structure spotting process was not performed for the conceptual design.

Foundations for the tubular steel structures will be concrete pier foundations. Site specific subsurface soil information is not available to perform detailed foundation analysis; however, the Cost Estimates consider foundation construction in both soil and rock conditions.

For purposes of the Cost Estimate, the right-of-way width for the HVDC Overhead Line will be 50 feet narrower than the right-of-way width specified for the Base Design. The reduction in right-of-way width reflects the narrower configuration of the HVDC Overhead Line structures. The resulting right-of-way width for the HVDC Overhead Line is 150 feet except in locations where the line parallels an existing 500kV AC overhead transmission line, in which case the right-of-way will be 175 feet wide. These widths will maintain consistency with assumptions used to develop the Base Design right-of-way width. Further analysis beyond the scope of this Study will be required to evaluate the potential for electrical interference issues due to the close proximity of parallel HVDC and AC transmission lines and possible adjustments in the right-of-way width.

The entire width of the right-of-way will be cleared of trees and vegetation during construction. Permanent access roads will be constructed along the entire length of the route except in agricultural areas.

5.1.2 Permitting, Right-of-Way Acquisition, and Mitigation
It is difficult to estimate costs for transmission line siting, permitting, right-of-way acquisition, and environmental mitigation due to the large variation in cost by geographic area and local conditions. The relative difference in these costs between the AC and HVDC overhead transmission line alternatives will be small since each alternative will utilize the same route and require essentially the same level of permitting.

5.1.3 Major Assumptions
The Cost Estimates are based on the following major assumptions. For a complete list of assumptions, see Appendix I.

- The estimate does not include costs related to transmission line siting, permitting, right-of-way acquisition, or environmental mitigation.
- The estimate does not include costs related to unique site conditions, such as long span crossings of rivers or gorges, wetland construction, or helicopter construction.
• The estimate is based on 32 miles of tubular steel construction and 68 miles of lattice tower construction.
• The estimate does not include costs for modification or relocation of existing nearby AC transmission lines or facilities other than the 27.3 miles of 138kV AC overhead transmission line which will be underbuilt on the HVDC Overhead Line structures.
• The estimate includes construction of access roads based on a linear length of 2 times the route length in mountainous areas (greater than 20% slope) and 1 times the route length in other areas.
• The estimate does not include utility overhead expenses or charges.

5.1.4 Estimated Costs
The Cost Estimate to construct the 100 mile long, HVDC Overhead Line segment between Welton Spring and Kemptown is $368 Million. See Appendix I – HVDC Overhead Transmission Estimate Summaries for a breakdown of the Cost Estimate.

5.2 Amos to Welton Spring
A Bipolar ± 600kV HVDC overhead transmission line (HVDC Overhead Line) was evaluated as an alternative for the Amos to Welton Spring segment of the Path Project. The route between Amos to Welton Spring used for this Study is approximately 176 miles long and is shown on the Estimated Route for Transmission Map included in Appendix C.

5.2.1 Conceptual Design
Similar to the Welton Spring to Kemptown HVDC Overhead Line segment, the Amos to Welton Spring HVDC Overhead Line segment will utilize a combination of lattice steel towers and tubular steel structures. All of the structures will be self supporting and the predominate structure type will be lattice steel towers. Tubular steel structures will be utilized only in agricultural areas with cultivated crops. The tubular steel tangent structures will be single shaft structures with the two (+) and (-) pole conductors supported on horizontal davit arms. The angle and dead end tubular structures will consist of 3-shaft structures. Additional structure types may be needed to deal with site specific design requirements but those have not been evaluated as part of the conceptual design. The quantity of angle and dead end structures was estimated from the Estimated Route for Transmission Maps. The average span length is estimated at 1350 feet which is consistent with the average span length in the PATH Project CPCN application to the West Virginia PSC.

Each pole conductor will consist of a bundle of three (3) sub-conductors arranged in a triangular pattern. The sub-conductors are 1272 kcmil 45/7 ACSR “Bittern” conductors. The pole-to-pole spacing is approximately 50 feet. The HVDC Overhead Line will also have a metallic return conductor which will be equivalent
in size to the pole conductors and capable of carrying 2,000 MW in the event that one of the pole conductors is inoperable. However, the metallic return conductor will be insulated for 35kV DC phase-to-ground, not ± 600kV HVDC. The HVDC Overhead Line will also have two (2) 1 inch diameter optical ground wires (OPGW) to be consistent with the Base Design.

Average structure heights were determined to maintain 35 feet of ground clearance with a conductor temperature of 212°F and 50 feet of ground clearance with a conductor temperature of 120°F at the average span length of 1350 feet. A detailed structure spotting process was not performed for the conceptual design.

Foundations for the tubular steel structures will be concrete pier foundations. Site specific subsurface soil information is not available to perform detailed foundation analysis; however, the Cost Estimates consider foundation construction in both soil and rock conditions.

For purposes of the Cost Estimate, the right-of-way width for the HVDC Overhead Line will be 50 feet narrower than the right-of-way width specified for the Base Design. The reduction in right-of-way width reflects the narrower configuration of the HVDC Overhead Line structures. The resulting right-of-way width for the HVDC Overhead Line is 150 feet except in locations where the line parallels an existing 500kV AC overhead transmission line, in which case the right-of-way will be 175 feet wide. These widths will maintain consistency with assumptions used to develop the Base Design right-of-way width. Further analysis beyond the scope of this Study will be required to evaluate the potential for electrical interference issues due to the close proximity of parallel HVDC and AC overhead transmission lines and possible adjustments in the right-of-way width.

The entire width of the right-of-way will be cleared of trees and vegetation during construction. Permanent access roads will be constructed along the entire length of the route except in agricultural areas.

5.2.2 Permitting, Right-of-Way Acquisition, and Mitigation
It is difficult to estimate costs for transmission line siting, permitting, right-of-way acquisition, and environmental mitigation due to the large variation in costs by geographic area and local conditions. The relative difference in these costs between the AC and HVDC overhead transmission line alternatives will be small since each alternative will utilize the same route and require essentially the same level of permitting.

5.2.3 Major Assumptions
The Cost Estimates are based on the following major assumptions. For a complete list of assumptions, see Appendix I.
• The estimate does not include costs related to overhead transmission line sitting, permitting, or right-of-way acquisition.
• The estimate does not include costs related to unique site conditions, such as long span crossings of rivers or gorges, wetland construction, or helicopter construction.
• The Amos to Welton Spring estimate is based on 3 miles of tubular steel construction and 173 miles of lattice steel construction. There is no AC transmission line underbuild on this segment of the HVDC Overhead Line.
• The estimate does not include costs for modification or relocation of existing nearby transmission lines.
• The estimate includes construction of access roads based on a linear length of 2 times the route length in mountainous areas (greater than 20% slope) and 1 times the route length in other areas.
• The estimate does not include utility overhead expenses or charges.

5.2.4 Estimated Costs
The Cost Estimate to construct the 176 mile long, HVDC Overhead Line segment between Amos and Welton Spring is $634 Million. See Appendix I – HVDC Overhead Transmission Line Cost Estimate Summaries for a breakdown of the Cost Estimate.
6.0 AC Overhead Transmission System

The basis of the AC overhead transmission system was taken from project information provided on the PATH Project web page (www.pathtransmission.com) and from the Joint Application for Certificates of Public Convenience and Necessity (CPCN application) filed by the PATH project before the Public Service Commission of West Virginia. However, the Cost Estimates in this Study are conceptual in nature and not intended to capture all of the design features of the PATH Project, most of which have not been determined at this time.

6.1 Welton Spring to Kemptown

A single circuit 765kV AC overhead transmission line (AC Overhead Line) was evaluated as an alternative for the Welton Spring to Kemptown segment of the PATH Project. The route between Welton Spring and Kemptown is approximately 100 miles long and is shown on the Estimated Route for Transmission Map included in Appendix C.

6.1.1 Conceptual Design

The AC Overhead Line will utilize a combination of lattice steel towers and tubular steel H-frame structures. All of the structures will be self supporting. The predominate structure type will be lattice steel towers with the H-frame structures being utilized only in agricultural areas with cultivated crops and where 138kV AC overhead transmission underbuild is needed. Other structure types may be needed to deal with site specific design requirements but those have not been evaluated as part of the conceptual design. The quantity of angle and dead end structures was estimated from the PATH Project transmission route maps. The average span length is estimated at 1350 feet which is consistent with the average span length in the PATH Project CPCN application to the West Virginia PSC.

Each phase conductor will consist of a bundle of six (6) sub-conductors arranged in a circular pattern. The sub-conductors are 957.2 kcmil 45/7 ACSR/TW “Kettle” conductors. The phase-to-phase spacing is 50 feet. The AC Overhead Line will also have two (2) 1 inch diameter optical ground wires (OPGW).

Average structure heights were determined to maintain 35 feet of ground clearance with a conductor temperature of 203°F and 50 feet of ground clearance with a conductor temperature of 120°F at the average span length of 1350 feet. A detailed structure spotting process was not performed for the conceptual design.

Foundations for the lattice towers and steel H-frames will be concrete pier foundations. Site specific subsurface soil information is not available to perform
detailed foundation analysis; however, the Cost Estimates consider foundation construction in both soil and rock conditions.

The right-of-way for the AC Overhead Line will be 200 feet wide except in locations where the line parallels an existing 500kV AC overhead transmission line, in which case the right-of-way will be 225 feet wide. The entire width of the right-of-way will be cleared of trees and vegetation during construction. Permanent access roads will be constructed along the entire length of the route except in agricultural areas.

6.1.2 Permitting, Right-of-Way Acquisition, and Mitigation
It is difficult to estimate costs for transmission line siting, permitting, right-of-way acquisition, and environmental mitigation due to the large variation in cost by geographic area and local conditions. The relative difference in these costs between the AC and HVDC overhead transmission line alternatives will be small since each alternative will utilize the same route and require essentially the same level of permitting.

6.1.3 Major Assumptions
The Cost Estimates are based on the following major assumptions. For a complete list of assumptions, see Appendix J.

- The estimate does not include costs related to transmission line siting, permitting, right-of-way acquisition, or environmental mitigation.
- The estimate does not include costs related to unique site conditions, such as long span crossings of rivers or gorges, wetland construction, or helicopter construction.
- The estimate is based on 32 miles of tubular H-frame construction and 68 miles of lattice tower construction.
- The estimate does not include costs for modification or relocation of existing nearby transmission lines or facilities other than the 27.3 miles of 138kV AC overhead transmission line which will be underbuilt on the AC Overhead Line structures.
- The estimate includes construction of access roads based on a linear length of 2 times the route length in mountainous areas (greater than 20% slope) and 1 times the route length in other areas.
- The estimate does not include utility overhead expenses or charges.

6.1.4 Estimated Costs
The Cost Estimate to construct the 100 mile long, AC Overhead Line segment between Welton Spring and Kemptown is $448 Million. See Appendix J – AC Overhead Transmission Estimate Summaries for a breakdown of the Cost Estimate.
6.2 Amos to Welton Spring
A single circuit 765kV AC overhead transmission line (AC Overhead Line) was evaluated as an alternative for the Amos to Welton Spring segment of the PATH Project. The general route between Amos to Welton Spring is approximately 176 miles long and is shown on the Estimated Route for Transmission Map included in Appendix C.

6.2.1 Conceptual Design
Similar to the Welton Spring to Kemptown segment, the Amos to Welton Spring segment of the AC Overhead Line will utilize a combination of lattice steel towers and tubular steel H-frame structures. All of the structures will be self supporting and the predominate structure type will be lattice steel towers. Tubular steel structures will be utilized only in agricultural areas with cultivated crops. The tangent tubular steel structures will be H-frame structures. The angle and dead end tubular structures will consist of 3-shaft structures. Other structure types may be needed to deal with site specific design requirements but those have not been evaluated as part of the conceptual design. The quantity of angle and dead end structures was estimated from the PATH Project transmission route maps. The average span length is estimated at 1350 feet which is consistent with the average span length in the PATH Project CPCN application to the West Virginia PSC.

Each phase conductor will consist of a bundle of six (6) sub-conductors arranged in a circular pattern. The sub-conductors are 957.2 kcmil 45/7 ACSR/TW “Kettle” conductors. The phase-to-phase spacing is 50 feet. The transmission line will also have two (2) 1 inch diameter optical ground wires (OPGW).

Average structure heights were determined to maintain 35 feet of ground clearance with a conductor temperature of 203°F and 50 feet of ground clearance with a conductor temperature of 120°F at the average span length of 1350 feet. A detailed structure spotting process was not performed for the conceptual design.

Foundations for the lattice towers and steel H-frames will be concrete pier foundations. Site specific subsurface soil information is not available to perform detailed foundation analysis; however, the Cost Estimates consider foundation construction in both soil and rock conditions.

The right-of-way for the AC Overhead Line will be 200 feet wide except in locations where the line parallels an existing 500kV AC overhead transmission line, in which case the right-of-way will be 225 feet wide. The entire width of the right-of-way will be cleared of trees and vegetation during construction. Permanent access roads will be constructed along the entire length of the route except in agricultural areas.
6.2.2 Permitting, Right-of-Way Acquisition, and Mitigation
It is difficult to estimate cost for transmission line sitting, permitting, right-of-way acquisition, and environmental mitigation due to the large variation in cost by geographic area and local conditions. The relative difference in these costs between the AC and HVDC overhead transmission alternatives will be small since each alternative will utilize the same route and require essentially the same level of permitting.

6.2.3 Major Assumptions
The Cost Estimates are based on the following major assumptions. For a complete list of assumptions, see Appendix J.

- The estimate does not include costs related to transmission line siting, permitting, or right-of-way acquisition.
- The estimate does not include costs related to unique site conditions, such as long span crossings of rivers or gorges, wetland construction, or helicopter construction.
- The estimate is based on 3 miles of tubular H-frame construction and 173 miles of lattice tower construction. There is no underbuild on this segment of the AC Overhead Line.
- The estimate does not include costs for modification or relocation of existing nearby transmission lines.
- The estimate includes construction of access roads based on a linear length of 2 times the route length in mountainous areas (greater than 20% slope) and 1 times the route length in other areas.
- The estimate does not include utility overhead expenses or charges.

6.2.4 Estimated Costs
The Cost Estimate to construct the 176 mile long, AC Overhead Line segment between Amos and Welton Spring is $756 Million. See Appendix J – AC Overhead Transmission Estimate Summaries for a breakdown of the cost estimate.
7.0 Comparison Summary
A relative comparison of the Base Design, Concept 1, and Concept 2, is provided in this section. The criteria used for the comparison includes structure height, right-of-way width (ROW), total costs, and operations.

7.1 Base Design and Concept 1 Comparison
Both the Base Design and Concept 1 are similar since both utilize overhead transmission conductors for the entire route; however, they differ in the technologies used to transmit the power, e.g., AC and HVDC respectively.

Both the Base Design and Concept 1 utilize a combination of lattice steel and tubular steel structures to support the overhead conductors and to provide sufficient electrical safety clearances above the ground. A relative comparison of the nominal structure dimensions and corresponding ROW widths are provided below:

<table>
<thead>
<tr>
<th></th>
<th>Maximum Structure Height Above Ground</th>
<th>Maximum Structure Width</th>
<th>ROW Width</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base Design</td>
<td>130’</td>
<td>150’</td>
<td>200’</td>
</tr>
<tr>
<td>Concept 1</td>
<td>150’</td>
<td>80’</td>
<td>150’</td>
</tr>
</tbody>
</table>

The structures for Concept 1 have a smaller width since only two pole conductors are required for HVDC transmission whereas three phase conductors are required for AC transmission. The result of the smaller width is that Concept 1 requires 50’ less ROW width than the Base Design.

The structures for the Base Design have a lower overall height since a metallic return conductor is not required for AC transmission whereas the metallic return conductor is required for the Bipolar HVDC transmission. The metallic return conductor is located above the pole conductors on the conceptual structure design which increases the structure height. The metallic return conductor will also provide extra protection against lightning strikes since it is located above the pole conductors.

A relative comparison of the costs for each major component of the Base Design and Concept 1 is provided below:
The Base Design has a lower overall total cost since the HVDC converter stations are not required to convert the AC grid voltage to HVDC for transmission. The cost savings from the HVDC Overhead Line due to the HVDC transmission only requiring two pole conductors whereby the AC transmission requires three phase conductors is not significant enough to offset the costs of the HVDC converter stations. Both the Base Design and Concept 1 will require similar AC interconnection substations to connect the transmission line in to the AC grid which is included in the cost comparison to show the overall total costs. The cost data for the AC interconnection substations was taken from the Joint Application for Certificates of Public Convenience and Necessity (CPCN application) filed by the PATH project before the Public Service Commission of West Virginia.

Although the Base Design has a cost advantage, Concept 1 has an operations advantage since the Concept 1 HVDC transmission system is a double circuit (Bipolar) design. Thus, only one-half of the HVDC power transmission capacity (2000 MW) will be taken out of service for maintenance of a single circuit (pole-to-metallic return) or for a single contingency event e.g., circuit fault (pole-to-ground). If the AC Overhead Line requires maintenance, or a single contingency event occurs, the entire power transmission capacity (5000 MW) of the respective segment will be taken out of service.

Concept 1 cannot be overloaded due to AC grid contingencies and resulting power surges; therefore, Concept 1 does not have a short time emergency power rating. Concept 1 will generally be set to a power dispatch control mode that is unaffected by the phase-angle differences between AC grid buses and will be maintained at the level determined by economic dispatch. Concept 1, unlike the Base Design, does not inherently take part in re-dispatch of load in connection with fault clearing and other AC grid contingencies. Concept 1 will be provided with special controls that allow the AC grid operator to preset desired HVDC re-dispatch in response to transmission line outages or other severe contingencies in the AC grid. The Base Design will have normal and emergency ratings in accordance with PJM transmission planning criteria to automatically re-dispatch load.
7.2 Base Design and Concept 2 Comparison

Both the Base Design and Concept 2 are similar since both utilize overhead transmission conductors with AC transmission for the Amos to Welton Spring segment of the route; therefore, a comparison of the total costs will be for the entire route; however, only a comparison of the structure configuration dimensions, right-of-way width (ROW), and operations for the Welton Spring to Kempton segment of the route will be made.

The Base Design utilizes a combination of lattice steel and tubular steel structures to support the overhead phase conductors and to provide sufficient electrical safety clearances above the ground. Concept 2 utilizes a combination of direct buried and HDD installation techniques to install the underground XLPE cable. Due to the thermal heat developed by the underground XLPE cable, the cables cannot be installed vertically on top of one another and will still require a relatively large ROW width. Additional permanent right-of-way width will also be required for future maintenance and repair work, and for handling and stockpiling materials during construction. A relative comparison of the nominal structure dimensions and corresponding ROW widths are provided below:

<table>
<thead>
<tr>
<th></th>
<th>Maximum Structure Height Above Ground</th>
<th>Maximum Structure Width</th>
<th>ROW Width</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base Design</td>
<td>130’</td>
<td>150’</td>
<td>200’</td>
</tr>
<tr>
<td>Concept 2, underground portion only</td>
<td>NA</td>
<td>NA</td>
<td>110’</td>
</tr>
</tbody>
</table>

The result of using underground HVDC transmission as opposed to overhead AC transmission is that Concept 2 requires 90’ less ROW width than the Base Design for the Welton Spring to Kemptown segment of the route.

Concept 2 also utilizes XLPE cable which does not require any intermediate dielectric fluid reservoirs along the Welton Spring to Kemptown segment of the route and will be a complete underground installation. The only structures that will appear above grade will be the terminators located at the HVDC converter stations.

A relative comparison of the costs for each major component of the Base Design and Concept 2 is provided below:

<table>
<thead>
<tr>
<th></th>
<th>Base Design</th>
<th>Concept 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>AC Overhead Line</td>
<td>$1204 M</td>
<td>$756 M</td>
</tr>
<tr>
<td>AC Interconnection Substations</td>
<td>$563 M</td>
<td>$563 M</td>
</tr>
<tr>
<td>HVDC Underground Line</td>
<td>NA</td>
<td>$884 M</td>
</tr>
<tr>
<td>HVDC Converter Stations</td>
<td>NA</td>
<td>$1392 M</td>
</tr>
</tbody>
</table>
The Base Design has a lower overall total cost since the HVDC converter stations are not required to convert the AC grid voltage to HVDC for transmission; and, the hybrid combination of the AC Overhead Line and the HVDC Underground Line costs are higher than the AC Overhead Line costs for the entire route. Unlike Concept 1, there is no cost savings from the hybrid transmission line to help offset the costs of the HVDC converter stations. Both the Base Design and Concept 2 will require similar AC interconnection substations to connect the transmission line in to the AC grid which is included in the cost comparison to show the overall total costs. The cost data for the AC interconnection substations was taken from the Joint Application for Certificates of Public Convenience and Necessity (CPCN application) filed by the PATH project before the Public Service Commission of West Virginia.

Although the Base Design has a cost advantage, Concept 2 has an operations advantage for the Welton Spring to Kemptown segment of the route since the Concept 2 HVDC transmission system is a triple circuit design. Only one-third of the HVDC power transmission capacity (1333 MW) will be taken out of service for maintenance of a single circuit or for a single contingency event e.g., circuit fault (pole-to-pole or pole-to-ground). If the AC Overhead Line requires maintenance, or a single contingency event occurs, the entire power transmission capacity (5000 MW) of this segment will be taken out of service.

Concept 2 is similar to Concept 1 since it also cannot be overloaded due to AC grid contingencies and resulting power surges; therefore, Concept 2 does not have a short time emergency power rating. See Concept 1 for further details.

### 7.3 Concept 1 and Concept 2 Comparison

Both Concept 1 and Concept 2 are similar since both utilize HVDC technology for transmission of power. Concept 1 utilizes all HVDC overhead transmission for the entire route; however, Concept 2 utilizes a hybrid of AC overhead transmission for the Amos to Welton Spring segment of the route and HVDC underground transmission for the Welton Spring to Kemptown segment of the route.

A relative comparison of the nominal structure dimensions and corresponding ROW widths for the Amos to Welton Spring segment are provided below:

<table>
<thead>
<tr>
<th></th>
<th>Maximum Structure Height Above Ground</th>
<th>Maximum Structure Width</th>
<th>ROW Width</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concept 1</td>
<td>150’</td>
<td>80’</td>
<td>150’</td>
</tr>
</tbody>
</table>
The result of the using HVDC overhead transmission as opposed to AC overhead transmission is that Concept 1 requires 50’ less ROW width than Concept 2 for the Amos to Welton Spring segment of the route.

A relative comparison of the nominal structure dimensions and corresponding ROW widths for the Welton Spring to Kemptown segment are provided below:

<table>
<thead>
<tr>
<th>Concept 2 maximum structure dimensions and ROW widths</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concept 2  underground portion only</td>
</tr>
<tr>
<td>130’</td>
</tr>
<tr>
<td>150’</td>
</tr>
<tr>
<td>200’</td>
</tr>
</tbody>
</table>

The result of the using HVDC underground transmission as opposed to HVDC overhead transmission is that Concept 2 requires 40’ less ROW width than Concept 1 for the Welton Spring to Kemptown segment of the route.

A relative comparison of the costs for each major component of Concept 1 and Concept 2 is provided below:

<table>
<thead>
<tr>
<th>Concept</th>
<th>AC Overhead Line</th>
<th>AC Interconnection Substations</th>
<th>HVDC Overhead Line</th>
<th>Overhead Tap Switchyard</th>
<th>HVDC Underground Line</th>
<th>HVDC Converter Stations (LCC)</th>
<th>HVDC Converter Stations (VSC)</th>
<th>DIFFERENTIAL TOTAL COSTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concept 1</td>
<td>NA</td>
<td>$563 M</td>
<td>$1002 M</td>
<td>$8 M</td>
<td>NA</td>
<td>$838 M</td>
<td>NA</td>
<td>$0</td>
</tr>
<tr>
<td>Concept 2</td>
<td>NA</td>
<td>$756 M</td>
<td>$563 M</td>
<td>NA</td>
<td>$884 M</td>
<td>NA</td>
<td>$1392 M</td>
<td>+$1484</td>
</tr>
</tbody>
</table>

Concept 1 has a lower overall total cost since the hybrid combination of AC Overhead Line and HVDC Underground Line costs are higher than the HVDC Overhead Line costs for the entire route. Also, the LCC HVDC technology has a cost savings when compared to the VSC HVDC technology. The savings from the AC Overhead Line costs are not enough to offset the HVDC Underground Line costs and the VSC converter stations. Both Concept 1 and Concept 2 will require similar AC interconnection substations to interconnect the transmission line into the AC grid which is included in the cost comparison to show the overall total costs. The cost data for the AC interconnection substations was taken from the Joint Application for Certificates of Public Convenience and Necessity (CPCN
application) filed by the PATH project before the Public Service Commission of West Virginia.

Although the Concept 1 has a cost advantage, Concept 2 has an operations advantage since the Concept 2 HVDC transmission system is a triple circuit design. Only one-third of the HVDC power transmission capacity (1333 MW) will be taken out of service for maintenance of a single circuit or for a single contingency event e.g., circuit fault (pole-to-pole or pole-to-ground).

Concept 1 also has an operations advantage for the entire route since the Concept 1 HVDC transmission system is a double circuit (Bipolar) design. Thus, only one-half of the HVDC power transmission capacity (2000 MW) will be taken out of service for maintenance of a single circuit (pole-to-metallic return) or for a single contingency event e.g., circuit fault (pole-to-ground). Concept 2 utilizes AC overhead transmission for the Amos to Welton Spring segment of the route; therefore, if the AC Overhead Line requires maintenance, or a single contingency event occurs, the entire power transmission capacity (5000 MVA) from Amos to Welton Spring will be taken out of service.
Appendix A
Block Diagrams for HVDC Concepts
PJM INTERCONNECTION
PATH PROJECT
BLOCK DIAGRAM - CONCEPT 1
AMOS -TO- WELTON SPRING -TO- KEMPTOWN

AMOS

2x LCC @ 2000MW EA
BI-POLE CONFIGURATION

OH x 2 CKT W/MR
± 600KV DC

OH TAP
DC SWITCHYARD

2x LCC @ 2000MW EA
BI-POLE CONFIGURATION

KEMPTOWN

WELTON SPRING

2x LCC @ 1000MW EA
BI-POLE CONFIGURATION
AC STATION AMOS

765KV AC

OH x 1 CKT

UG x 3 CKTS

± 400KV DC

SYMMETRICAL MONO-POLE CONFIGURATION

3X VSC @ 1333MW EA

AC STATION WELTON SPRING

3X VSC @ 1333MW EA

SYMMETRICAL MONO-POLE CONFIGURATION

AC STATION KEMPTOWN

PJM INTERCONNECTION

PATH PROJECT

BLOCK DIAGRAM - CONCEPT 2

AC OVERHEAD: AMOS -TO- WELTON SPRING

DC UNDERGROUND: WELTON SPRING -TO- KEMPTOWN

C 06/15/09 AMK REVISED TITLE BLOCK

B 06/04/09 AMK 06/04/09 CONFERENCE CALL COMMENTS

A 06/02/09 AMK INITIAL ISSUE

DATE 06/02/09 CHECKED

SCALE NONE APPROVED

DRAWN JDC APPROVED

SK090528-C2
AMOS

OH x 3 CKTS
± 400KV DC

O H-U G T A P / T R A N S I T I O N S W I T C H Y A R D

UG x 3 CKTS
± 400KV DC

KEMPTOWN

3X VSC @ 1333MW EA
SYMMETRICAL MONO-POLE
CONFIGURATION

WELTON SPRING

3X VSC @ 1333MW EA
SYMMETRICAL MONO-POLE
CONFIGURATION

PJM INTERCONNECTION
PATH PROJECT

BLOCK DIAGRAM - CONCEPT 3
DC OVERHEAD: AMOS -TO- WELTON SPRING
DC UNDERGROUND: WELTON SPRING -TO- KEMPTOWN

REV. DATE BY CHK. DESCRIPTION

C 06/15/09 AMK REVISED TITLE BLOCK
B 06/04/09 AMK 06/04/09 CONFERENCE CALL COMMENTS
A 06/02/09 AMK INITIAL ISSUE
Appendix B
HVDC Converter Station Layouts
Concept 1

2x1000 MW Classic LCC
Converter Station
At Welton Spring
Concept 1

2x2000 MW Classic LCC Converter Station At Kemptown
Concept 2

1333 MW VSC
Converter Station
At Welton Spring
And Kemptown
Appendix C
Estimated Route for Transmission Line Map
Appendix D

Typical Underground Transmission Cross Sections
DIRECT BURIED HVDC
UNDERGROUND CABLE INSTALLATION
TYPICAL CROSS-SECTION

SCALE: NTS

GRADE
NATIVE BACKFILL
CONCRETE SLAB
CABLE BEDDING SAND
400 KV DC CABLE

CORRECTIVE BACKFILL

PERMANENT R-O-W
TOTAL CONSTRUCTION EASEMENT
SPACE EACH SIDE FOR FUTURE MAINTENANCE AND REPAIR

MIN.
20'-0"

MIN.
10'-0"
4'-8"

MIN.
33'-0"
(TYP.)
33'-0"

MIN.
1'-0"
1'-8"

MIN.
10'-0"
110'-0"

20'-0"

90'-0"

33'-0"
(TYP.)

06-17-09
CHECKED

06-16-09
DATE

TEMPORARY CONSTRUCTION EASEMENT FOR HANDLING AND STOCKPILING MATERIALS
HVDC UNDERGROUND CABLE
TYPICAL SPLICE BOX

SCALE: 1/2"=1'-0"
HORIZONTAL DIRECTIONAL DRILL FOR UNDERGROUND CABLE TYPICAL CROSS-SECTION

SCALE: NTS

UNDISTURBED SOIL

10" HDPE SDR-9 PIPE

400KV DC CABLE

VARIES

75'-0" (MIN.)

HORIZONTAL DIRECTIONAL DRILL PATH

ADDITIONAL SPACE FOR FIELD ADJUSTMENT OF DRILL PATH

SPARE 10" CONDUIT

CONDUIT FOR COMMUNICATIONS

12" HDPE 3000-150 PIPE 400KV DC CABLE

R-O-W REQUIRED

25'-0" 25'-0"

ADDITIONAL SPACE FOR FIELD ADJUSTMENT OF DRILL PATH

ASSUMED SCALES
Appendix E

Typical HVDC Overhead Transmission Cross Sections
PJM INTERCONNECTION
PATH PROJECT

TYPICAL STRUCTURE AND RIGHT OF WAY
±600kV DC SINGLE CIRCUIT

DATE 07/23/09  CHECKED
SCALE NONE  APPROVED
DRAWN JSF  APPROVED

A 07/23/09 TCC - INITIAL ISSUE

SK-DC02
Appendix F
Typical AC Overhead Transmission Cross Sections
PROPOSED 765kV
PROPOSED 765kV
NOTE A:
ALL UNDERBUILD DIMENSIONS SUBJECT TO MODIFICATIONS RESULTING FROM
DETAILED ENGINEERING ANALYSIS.

PROPOSED 765kV

TYPICAL STRUCTURE AND RIGHT OF WAY
765kV SINGLE CIRCUIT H1TBB
SELF-SUPPORTING H-FRAME w/ 138kV UNDERBUILD

EXHIBIT RLP-5
Appendix G
HVDC Converter Station Cost Estimate Summary
### EPC Cost Estimate

**Concept 1: 2 x 2000 MW Classic DC Converter Units at Kempton**

<table>
<thead>
<tr>
<th>Description</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>4000 MW (2 x 2000 MW) HVDC Classic Converter Units</td>
<td>$240,000,000</td>
</tr>
<tr>
<td>Site Development for 2 x 2000 MW Classic Converter Units</td>
<td>$5,568,471</td>
</tr>
<tr>
<td>Balance of Plant for 2 x 2000 MW Classic Converter Units</td>
<td>$54,095,911</td>
</tr>
<tr>
<td><strong>Total EPC Cost</strong></td>
<td><strong>$299,664,382</strong></td>
</tr>
</tbody>
</table>

### EPC Cost Estimate

**Concept 1: 2 x 2000 MW Classic DC Converter Units at Amos**

<table>
<thead>
<tr>
<th>Description</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>4000 MW (2 x 2000 MW) HVDC Classic Converter Units</td>
<td>$240,000,000</td>
</tr>
<tr>
<td>Site Development for 2 x 2000 MW Classic Converter Units</td>
<td>$5,568,471</td>
</tr>
<tr>
<td>Balance of Plant for 2 x 2000 MW Classic Converter Units</td>
<td>$54,095,911</td>
</tr>
<tr>
<td><strong>Total EPC Cost</strong></td>
<td><strong>$299,664,382</strong></td>
</tr>
</tbody>
</table>

### EPC Cost Estimate

**Concept 1: 2 x 1000 MW Classic DC Converter Units at Welton Spring**

<table>
<thead>
<tr>
<th>Description</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>2000 MW (2 x 1000 MW) HVDC Classic Converter Units</td>
<td>$180,000,000</td>
</tr>
<tr>
<td>Site Development for 2 x 1000 MW Classic Converter Units</td>
<td>$4,092,550</td>
</tr>
<tr>
<td>Balance of Plant for 2 x 1000 MW Classic Converter Units</td>
<td>$54,177,508</td>
</tr>
<tr>
<td><strong>Total EPC Cost</strong></td>
<td><strong>$238,270,058</strong></td>
</tr>
</tbody>
</table>

### EPC Cost Estimate

**Concept 1: Overhead Tap DC Switchyard**

<table>
<thead>
<tr>
<th>Description</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Site Development for OH Tap DC Switchyard</td>
<td>$2,493,656</td>
</tr>
<tr>
<td>Balance of Plant for OH Tap DC Switchyard</td>
<td>$5,105,785</td>
</tr>
<tr>
<td><strong>Total EPC Cost</strong></td>
<td><strong>$7,599,441</strong></td>
</tr>
</tbody>
</table>

**Total EPC Price for Concept 1** $845,198,263
### EPC Cost Estimate
**Concept 2: 3 - 1333 MW VSC DC Converter Units at Welton Spring**

<table>
<thead>
<tr>
<th>Description</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 HVDC Voltage Source Converter Units rated 800kV (+/- 400kV), 1333 MW each</td>
<td>$448,000,000</td>
</tr>
<tr>
<td>Site Development for 3 - 1333 MW VSC Converter Units</td>
<td>$5,075,635</td>
</tr>
<tr>
<td>Balance of Plant for 3 - 1333 MW VSC Converter Units</td>
<td>$242,739,420</td>
</tr>
<tr>
<td><strong>Total EPC Cost</strong></td>
<td><strong>$695,815,055</strong></td>
</tr>
</tbody>
</table>

### EPC Cost Estimate
**Concept 2: 3 - 1333 MW VSC DC Converter Units at Kemptown**

<table>
<thead>
<tr>
<th>Description</th>
<th>Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>3 HVDC Voltage Source Converter Units rated 800kV (+/- 400kV), 1333 MW each</td>
<td>$448,000,000</td>
</tr>
<tr>
<td>Site Development for 3 - 1333 MW VSC Converter Units</td>
<td>$5,075,635</td>
</tr>
<tr>
<td>Balance of Plant for 3 - 1333 MW VSC Converter Units</td>
<td>$242,739,420</td>
</tr>
<tr>
<td><strong>Total EPC Cost</strong></td>
<td><strong>$695,815,055</strong></td>
</tr>
</tbody>
</table>

**Total EPC Price for Concept 2**  $1,391,630,111
Appendix H

HVDC Underground Transmission Cost Estimate Summary
## Item

<table>
<thead>
<tr>
<th>Item</th>
<th>Qty</th>
<th>Unit</th>
<th>Total Unit Cost</th>
<th>Total Labor Cost</th>
<th>TOTAL COST</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cable System Furnish and Install</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Cable System Communications (FO) Subtotal</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Distributed Temperature Sensing System Subtotal</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Civil Work</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>General Subtotal</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Overhead to Underground Subtotal</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Splicing Vault Subtotal</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Direct Buried - Agricultural</td>
<td>149463 Feet</td>
<td>$17,145,515</td>
<td>$41,368,556</td>
<td>$58,514,071</td>
<td></td>
</tr>
<tr>
<td>Direct Buried cost per route foot (3 Trenches)</td>
<td>$30.115</td>
<td>$301.15</td>
<td>$305.74</td>
<td>$306.96</td>
<td></td>
</tr>
<tr>
<td>Direct Buried - Cleared Corridor</td>
<td>298320 Feet</td>
<td>$34,221,512</td>
<td>$84,350,383</td>
<td>$118,571,895</td>
<td></td>
</tr>
<tr>
<td>Direct Buried cost per route foot (3 Trenches)</td>
<td>$305.74</td>
<td>$305.74</td>
<td>$306.96</td>
<td>$306.96</td>
<td></td>
</tr>
<tr>
<td>Direct Buried - Light Clearing</td>
<td>10758 Feet</td>
<td>$1,234,094</td>
<td>$3,058,863</td>
<td>$4,292,957</td>
<td></td>
</tr>
<tr>
<td>Direct Buried cost per route foot (3 Trenches)</td>
<td>$306.96</td>
<td>$306.96</td>
<td>$306.96</td>
<td>$306.96</td>
<td></td>
</tr>
<tr>
<td>Direct Buried - Heavy Clearing</td>
<td>24494 Feet</td>
<td>$2,809,807</td>
<td>$7,994,301</td>
<td>$10,804,109</td>
<td></td>
</tr>
<tr>
<td>Direct Buried cost per route foot (3 Trenches)</td>
<td>$339.30</td>
<td>$339.30</td>
<td>$339.30</td>
<td>$339.30</td>
<td></td>
</tr>
<tr>
<td>HDD Installation Subtotal</td>
<td>52700 Feet</td>
<td>$26,118,752</td>
<td>$79,402,635</td>
<td>$105,521,387</td>
<td></td>
</tr>
<tr>
<td>HDD Ductbank cost per route foot (3 Bores)</td>
<td>$1,540.53</td>
<td>$1,540.53</td>
<td>$1,540.53</td>
<td>$1,540.53</td>
<td></td>
</tr>
<tr>
<td>Estimated Labor &amp; Material Cost</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Escalation (Not Included)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Estimated Project Cost</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>State Sales Tax</td>
<td></td>
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<tr>
<td>Row Acquisition</td>
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<td></td>
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<tr>
<td>Mitigation</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Topographic Surveying/Soil Exploration @ 40,000/mi</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$4,056,000</td>
</tr>
<tr>
<td>Engineering and Technical Support During Construction</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$7,755,000</td>
</tr>
<tr>
<td>Construction Management</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$15,120,000</td>
</tr>
<tr>
<td>Estimated Total Project Cost</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Underground Project Total (rounded)**: $884,000,000
Black & Veatch

Client: PJM
Project: PATH, Welton Springs to Kemptown Segment
Assumptions: B&V File No. 164996

General

1. The estimate is based on a installation 101.4 miles long.
2. The estimate does not include ROW acquisition costs.
3. The estimate does not include costs for environmental mitigation or habitat restoration.
4. The estimate does not include costs related to contaminated or hazardous soils or water.
5. The estimate does not include allowances for existing facility relocations.
6. The estimate does not include allowances for work hour/location restrictions.
7. The estimate is based on 2009 dollars and 7.5 Swedish Kronas to the Dollar.
8. The estimate does not include overhead or internal costs for the utility.
9. The estimate does not include state sales tax.

Cable & Accessories

10. The estimate assumes three (3) 400kV DC circuits, 2 cables per circuit.
11. The cables are estimated as 400kV DC, 2000 sq. mm Cu Cable for 90% of the route
    The cables are estimated as 400kV DC, 2500 sq. mm Cu Cable for 10% of the route (HDD)
12. The estimate includes 4000 feet of spare cable.
13. The estimate includes (12) AIS cable terminations, and (6) spare terminations.
14. The estimate includes (1,608) single-phase cable joints, with 12 spare joints.
15. The estimate does not include surge arrestors.
16. The estimate does not include optical fiber inside the power cable for temperature monitoring.

Communications

17. The fiber optic cables are installed direct buried in the same trench as the power cable.
18. Fiber-optic cables are estimated as three (3) 48 fiber, single mode, armored cables.
19. Separate splicing enclosures for each communications cable are included in the estimate.

Temperature Monitoring

20. The estimate does not include cable temperature monitoring equipment.

Overhead to Underground Transition

21. The estimate includes two sets of (6) single cable termination structures
22. The estimate does not include provisions for overhead transmission connections
23. The estimate does not include concrete encased conduit sweeps at the cable terminations

Splice Housings

24. The estimate includes (1608) 16’x6’x3’-6” precast concrete splice housings.
25. Each splice housing is assumed to hold (1) splice.

Direct Buried Installation

26. The estimate does not include conduits in the direct buried sections.
27. The estimate does not include traffic control.
28. The estimate includes soil erosion and sediment control measures for green spaces.
29. The cables are installed in (3) 2.5’ wide by 5’ deep trenches.
30. The cables are installed in a thermal sand cable bedding material
31. The estimate includes a 9” thick concrete cap installed above the cable bedding sand.
32. The estimate assumes the top 18” of the trench will consist of native soil backfill or roadbed and pavement.
33. The estimate includes significant vegetation clearing and restoration 75’ wide for 6.68 miles of the route.
34. The estimate assumes the work in the existing corridors does not require extensive clearing.
35. The estimate does not include pavement replacement in roadways.
36. The estimate includes minor dewatering for 25% of the trench.
37. The estimate does not include shoring for the trenches.
38. The estimate does not include rock excavation.

HDD Installation

39. The estimate includes (62) sets of HDD installations, averaging 850 feet long.
40. Each HDD installation consists of three bundles FPVC or HDPE conduits pulled directly into separate borehole
41. The HDD installations do not include a casing.
42. The estimate does not include grouting of the bore holes.

Engineering & Construction Management

43. The estimate includes surveying, and soil exploration.
44. The estimate includes approximate engineering costs.
45. The estimate includes construction management based on a 36 month construction duration.
Appendix I

HVDC Overhead Transmission Cost Estimate Summary
### EPC Indicative Cost Estimate
#### Amos to Welton Spring: DC Overhead Option

<table>
<thead>
<tr>
<th>Description</th>
<th>Materials</th>
<th>Labor</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Project Management, Engineering, Construction Management</td>
<td>$71,114,481</td>
<td>$71,114,481</td>
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</tr>
<tr>
<td>Structures &amp; Hardware</td>
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<td>$88,239,373</td>
<td>$177,180,419</td>
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<td>Conductor</td>
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<td>$34,953,492</td>
<td>$57,669,443</td>
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<tr>
<td>OPGW</td>
<td>$13,138,704</td>
<td>$6,205,484</td>
<td>$19,344,187</td>
</tr>
<tr>
<td>Foundations</td>
<td>$56,098,696</td>
<td>$56,098,696</td>
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</tr>
<tr>
<td>Access, Clearing, Sitework, Material Management &amp; Laydown</td>
<td>$253,034,502</td>
<td>$253,034,502</td>
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<tr>
<td><strong>Total Estimated EPC Cost</strong></td>
<td></td>
<td></td>
<td><strong>$634,441,728</strong></td>
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### EPC Indicative Cost Estimate
#### Welton Spring to Kemptown: DC Overhead Option

<table>
<thead>
<tr>
<th>Description</th>
<th>Materials</th>
<th>Labor</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Project Management, Engineering, Construction Management</td>
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<td>Structures &amp; Hardware</td>
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<td>OPGW</td>
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<td>$11,037,893</td>
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<tr>
<td>Foundations</td>
<td>$51,292,886</td>
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<tr>
<td>Access, Clearing, Sitework, Material Management &amp; Laydown</td>
<td>$104,359,004</td>
<td>$104,359,004</td>
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</tr>
<tr>
<td><strong>Total Estimated EPC Cost</strong></td>
<td></td>
<td></td>
<td><strong>$368,155,700</strong></td>
</tr>
</tbody>
</table>
The estimate assumes primarily 4 legged self supporting lattice steel towers except in areas with cultivated crops or 138kV underbuild in which case single shaft tubular steel davit arm structures are assumed. The Amos to Welton Spring segment has 3 miles of cultivated crop and no sections with 138kV underbuild. The Welton Spring to Kempton segment has 5 miles of cultivated crops and 27.4 miles of 138kV underbuild. The quantity of structures is based on an average span length of 1365 feet. All structures have a zero degree shielding angle.

The phase conductors are a bundle of three (3) 1272 kcmil 45/7 ACSR "Bittern" conductors. The estimate includes a metallic return cable capable of carrying 2,000MW. The metallic return consists of a bundle of three (3) 1272 kcmil 45/7 ACSR "Bittern" conductors insulated at 35kV. The estimate includes two (2) 1" diameter OPGW cables. The 138kV underbuild conductor is assumed to be one (1) 954 kcmil 54/7 ACSR "Cardinal" conductor per phase.

The estimate assumes all structures are supported on drilled pier foundations. The estimate assumes 20% of the foundations will be constructed in rock and the remaining 80% will be in soil. The estimate assumes all foundations can be excavated with drilled pier augers. No rock blasting is included.

The estimate assumes a 175' wide ROW where the DC line parallels an existing 500kV AC line and a 150' wide ROW elsewhere. No considerations have been included for potential AC/DC interactions between adjacent circuits either on the same structure or on adjacent structures. The estimate includes construction of access roads based on a linear length of 2 times the route length in mountainous areas (greater than 20% slope) and 1 times the route length in other areas. The estimate assumes clearing of the entire width of the ROW. The acreage of clearing was estimated from Google Earth images of the line route. Restoration costs for regrading the ROW are included. No other restoration costs are included.

The estimate includes costs for transmission line LIDAR surveying, construction staking surveying, and soil boring. The estimate includes design engineering costs at approximately 1% of the project cost. The estimate includes on site construction management based on a 48 month construction duration for the Amos to Welton Spring section and a 29 month construction duration for the Welton Spring to Kempton section. The construction management includes material marshalling yards and materials management and control.
Appendix J
AC Overhead Transmission Cost Estimate Summary
### EPC Indicative Cost Estimate

#### Amos to Welton Spring: AC Overhead Option

<table>
<thead>
<tr>
<th>Description</th>
<th>Materials</th>
<th>Labor</th>
<th>Total</th>
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<tr>
<td>OPGW</td>
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<td>$19,344,187</td>
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<td>Foundations</td>
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<td></td>
<td>$69,988,601</td>
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<td>Access, Clearing, Sitework, Material Management &amp; Laydown</td>
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<td>$255,417,042</td>
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</table>

**Total Estimated EPC Cost**

- $755,600,706

### EPC Indicative Cost Estimate

#### Welton Spring to Kemptown: AC Overhead Option

<table>
<thead>
<tr>
<th>Description</th>
<th>Materials</th>
<th>Labor</th>
<th>Total</th>
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</thead>
<tbody>
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<tr>
<td>Foundations</td>
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<td></td>
<td>$57,141,203</td>
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<tr>
<td>Access, Clearing, Sitework, Material Management &amp; Laydown</td>
<td></td>
<td>$105,224,092</td>
<td>$105,224,092</td>
</tr>
</tbody>
</table>

**Total Estimated EPC Cost**

- $447,512,619
General

1. The estimate is based on a single circuit 765 kV AC overhead transmission line. The Amos to Welton Spring segment is 176 miles long and the Welton Spring to Kempton segment is 100 miles long.
2. The estimate does not include costs for transmission line sitting, permitting, ROW acquisition, or real estate.
3. The estimate does not include costs for environmental mitigation or habitat restoration.
4. The estimate does not include costs related to contaminated or hazardous soils or water.
5. The estimate does not include allowances for relocation or modification to existing facilities.
6. The estimate does not include allowances for work hour/location restrictions.
7. The estimate is based on 2009 dollars.
8. The estimate includes a 10% Prime Contractor's profit.
9. The estimate does not include overhead or internal costs for the utility.
10. The estimate does not include state sales tax.

Structures, Wires, & Hardware

11. The estimate assumes primarily 4 legged self supporting lattice steel towers except in areas with cultivated crops or 138kV underbuild in which case tubular steel H-frame structures are assumed.
12. The Amos to Welton Spring segment has 3 miles of cultivated crop and no sections with 138kV underbuild. The Welton Spring to Kempton segment has 5 miles of cultivated crops and 27.4 miles of 138kV underbuild.
13. Tubular steel dead end structures are assumed to be three (3) self supporting poles.
14. The quantity of structures is based on an average span length of 1365 feet.
15. The quantity of angle structures is based on the line route map shown in Appendix C.
16. All structures have a zero degree shielding angle.
17. The phase conductors are a bundle of six (6) 957.2 kcmil 45/7 ACSR/TW "Kettle" conductors.
18. The estimate includes two (2) 1" diameter OPGW cables.
19. The 138kV underbuild conductor is assumed to be one (1) 954 kcmil 54/7 ACSR "Cardinal" conductor per phase.

Foundations

20. The estimate assumes all structures are supported on drilled pier foundations.
21. The estimate assumes 20% of the foundations will be constructed in rock and the remaining 80% will be in soil.
22. The estimate assumes all foundations can be excavated with drilled pier augers. No rock blasting is included.

Right-of-Way, Clearing, Access, etc

23. The estimate assumes a 225' wide ROW where the AC line parallels an existing 500kV AC line and a 200' wide ROW elsewhere.
24. The estimate includes construction of access roads based on a linear length of 2 times the route length in mountainous areas (greater than 20% slope) and 1 times the route length in other areas.
25. The estimate assumes clearing of the entire width of the ROW. The acreage of clearing was estimated from Google Earth images of the line route.
26. Restoration costs for regrading the ROW are included. No other restoration costs are included.

Engineering & Construction Management

27. The estimate includes costs for transmission line LIDAR surveying, construction staking surveying, and soil boring.
28. The estimate includes design engineering costs at 1% of the project cost.
29. The estimate includes on site construction management based on a 48 month construction duration for the Amos to Welton Spring section and a 29 month construction duration for the Welton Spring to Kempton section.
30. The construction management includes material marshalling yards and materials management and control.