SOLUTION REPORT
FOR THE
INTERSTATE RELIABILITY PROJECT

AUGUST, 2008

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TABLE OF CONTENTS

APPENDICES

Appendix Item 1:

Interstate Reliability Options Cost Spreadsheet

Appendix Item 2:

GE Energy, *Applicability of an HVDC Option in the NEEWS Upgrade,* (2008)

Appendix Item 3:

Comparative Routing Analysis of Option A and Option C-2

Table of Figures

LIST OF TABLES

1.0 PURPOSE OF THIS SOLUTION REPORT

This report was prepared by The Connecticut Light and Power Company (CL&P) and National Grid USA (National Grid) (collectively, the Transmission Owners or TOs) to explain their joint development of the Interstate Reliability Project (Project), a new 345-kV electric transmission line connecting substations in Connecticut, Rhode Island, and Massachusetts and related system improvements. This Solution Report for the Interstate Reliability Project (The Interstate Solution Report) will document the conformity of that proposed Project to the goals and requirements articulated in two reports prepared by ISO-NE, which in turn summarize a multi-year planning effort undertaken co-operatively by the TOs and Independent System Operator – New England (ISO-NE). These two reports, which will be referenced throughout this paper, are: *Southern New England Transmission Reliability Report 1: Needs Analysis* (January, 2008) (the *Needs Analysis)*; and *New England East-West Solutions (Formerly Southern New England Transmission Reliability) Report 2, Options Analysis*, (Redacted) June, 2008 (the *Options Analysis)*.

1.1 BACKGROUND OF THE INTERSTATE RELIABILITY COMPONENT OF THE NEW ENGLAND EAST-WEST SOLUTION (NEEWS)

In its 2003 Regional Transmission Expansion Plan (RTEP03), ISO-NE recognized that:

> As New England load levels continue to increase, the inability to import sufficient power into Connecticut from Southeast Massachusetts and Rhode Island will begin to have serious impacts on both system reliability and economic congestion. The current Connecticut Import limitation is of concern even with all existing and planned generating units within Connecticut in-service. Any retirement, deactivation of a relatively small block of older fossil units, the inability of planned units to achieve commercial status, or the unavailability of one of the nuclear units could cause problems as early as 2003. In addition, the congestion analyses performed indicate that, by 2006, the East-West interface will become constrained.

(RTEP03, Executive Summary §5.4.3)

Some of the generation units planned at the time of RTEP03 have in fact been delayed in achieving commercial status[1]. However, the more serious risk of a prolonged forced outage of one of the nuclear units has not been realized[2].

In 2003, to address the reliability issues identified in the passage quoted above from the RTEP, "preliminary transmission studies" were examining "a number of alternate remedies, which [would] improve both the Connecticut Import and East-West transfer limits." *Id.* At that time, ISO-NE recognized that "a 345 kV transmission line from Massachusetts to Rhode Island to Connecticut is the most practical upgrade to resolve both the Connecticut Import and East-West transfer problems;" and that "preliminary results favor a Millbury to Sherman to Lake Road to Card 345 kV line over existing right-of-way." *Id.* Accordingly, ISO-NE "recommend[ed] that completion of the required detailed transmission studies for the project be undertaken immediately, and that the required approvals for its construction be pursued." *Id.*

CL&P, through its affiliate, Northeast Utilities Service Company (NUSCO) and National Grid acted on that recommendation and continued to study a line that would connect CL&P's Card Street and Lake Road Substations to National Grid substations in Rhode Island and in Millbury, Massachusetts. In RTEP04, ISO-NE recognized that:

Considerable work has been done to identify a preferred alternative to address CT import needs. Analyses continue to support a 345 kV path either from Card to Lake Road to Sherman or W. Farnum to Millbury. Additional analyses are being performed to identify which refinements best facilitate utilization of the generation connected to the 345 kV network while best serving Rhode Island's access to it.

At the time, the new line was projected to be in service by 2008 and will provide 800 MW to 1,000 MW of improved transfer capability. (RTEP04 §14.2.8)

Two years later ISO-NE noted that:

> "However, in the course of 2004 and 2005, ISO-NE determined that a number of reliability problems that regional stakeholders had initially pursued independently were interrelated, and that, in particular there were "many interrelationships among the transmission reinforcement projects in

[1] In 2003, there were three generating projects approved by the Connecticut Siting Council that have not yet been constructed – the 544-MW Northeast Generating LLC project in Meriden; the 512-MW Towantic Energy LLC project in Oxford; and the 520-MW Kleen Energy Systems, LLC project in Middletown.

[2] There is, however, a past history of such risks being realized. All three Millstone units (2600+ MW) suffered a prolonged forced outage in 1996, and Millstone Unit 1 (660 MW) never came back on line. In addition, the Connecticut Yankee Plant (591 MW) was permanently retired from service in 1996.

> the region, such as for the Springfield area, Rhode Island, and for the Connecticut-Rhode Island-Massachusetts 345 kV bulk supply." (ISO-NE 2006 Regional System Plan (RSP05), §8.2.2) Accordingly, ISO formed a working group to develop a "comprehensive analysis of system needs in the southern New England region." (RTEP 06, §8.2.2, fn. 127)

The objective of the analysis was to develop a 10-year plan that would ensure that the SNE region continues to comply with criteria and reliability standards established by the North American Electric Reliability Corporation (NERC), the Northeast Power Coordinating Council (NPCC), and ISO-NE.[3] Although membership in the working group was open to all regional transmission owners, those who participated, in addition to ISO-NE itself, were NUSCO and National Grid. Meanwhile, the planning previously underway at NUSCO and National Grid relating to a potential Card – Sherman or West Farnum – Millbury 345-kV line was terminated as an independent project, and became subsumed in the much larger regional planning effort. As part of this effort, on August 7, 2006, the ISO-NE issued a draft of the *Needs Analysis.* The *Needs Analysis* was later published, with minor changes, in final form in January, 2008.[4] The *Needs Analysis* described the ongoing effort of which it was a part as "one of the most geographically comprehensive planning efforts to date in New England, addressing five interrelated problems in three states and multiple service territories." *Needs Analysis*, at i.

1.2.1 Summary of the Needs Analysis

In Section 1.1 of the *Needs Analysis* (pages 1-3), ISO-NE described the Southern New England (SNE) region and its problems as follows:

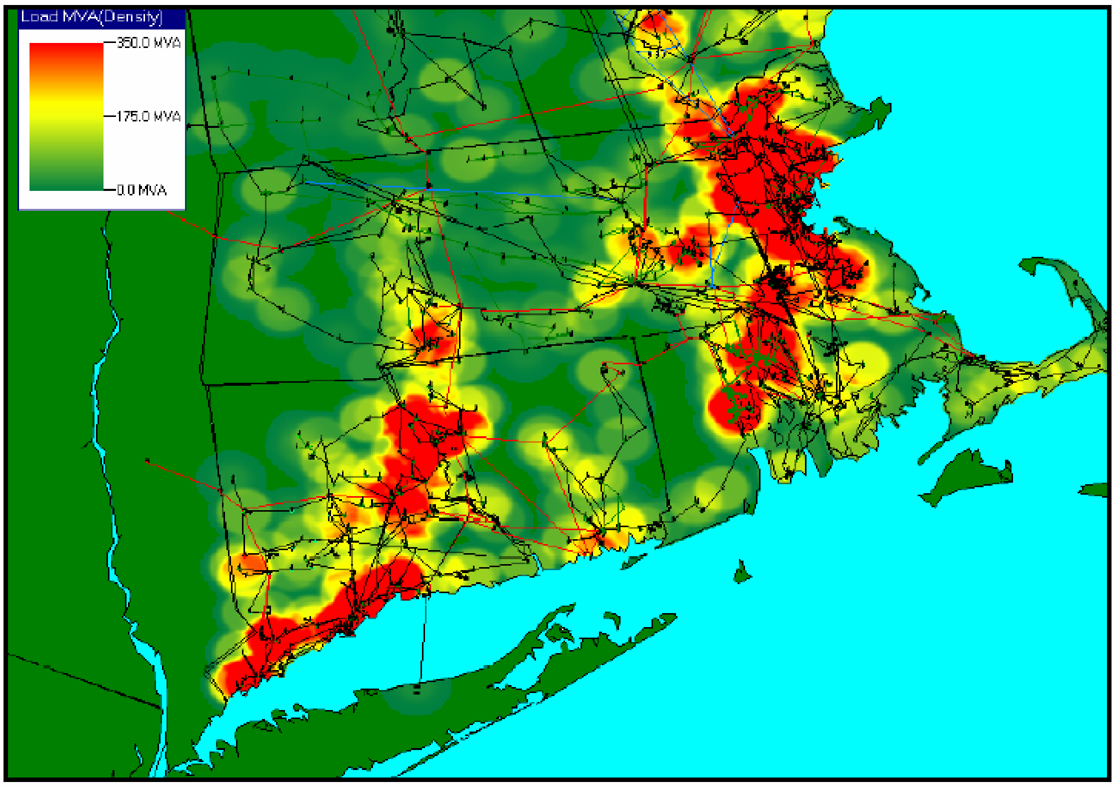
> The map shown in Figure 1-1 depicts the load density for the geographic area of southern New England, namely Massachusetts, Rhode Island, and Connecticut. As shown in this figure, a substantial number of significant load pockets exist—Boston and its suburbs, central Massachusetts, Springfield, Rhode Island, Hartford/central Connecticut, and Southwest Connecticut. The load pockets of Springfield, Rhode Island, Hartford/central

[3] The ISO system must comply with NERC and NPCC criteria and standards and ISO planning and operating procedures. As certified by the Federal Energy Regulatory Commission in 2006, NERC is the "electric reliability organization" (ERO) whose mission is to improve the reliability and security of the bulk power system in North America. Information on NERC requirements is available online at http://www.nerc.com (Princeton, NJ: NERC, 2007). NPCC is the cross-border regional entity and criteria services corporation for northeastern North America. NPCC's mission is to promote and enhance the reliable and efficient operation of the international, interconnected bulk power system in the geographic area that includes New York State, the six New England states, Ontario, Québec, and the Maritime provinces of Canada. Additional information on NPCC is available online at http://www.npcc-cbre.org/default.aspx (New York: NPCC Inc., 2007). Information about ISO New England Planning Procedure No. 3 (PP 3), *Reliability Standards for the New England Area Bulk Power Supply System*, is available online at http://www.iso-ne.com/rules_proceds/isone_plan/PP3_R3.doc (Holyoke, MA: ISO New England, 2006).

[4] References in this document to the Needs Analysis are to the document in its final published form.

Connecticut, and Connecticut as a whole are primary areas of concern in this study with respect to the ability of the existing transmission and generation systems to reliably serve projected load requirements in these areas.

Figure 1-1: Southern New England Load Concentrations[5]



Southern New England accounts for approximately 80% of the New England load. The 345 kV bulk transmission network is the key infrastructure that integrates the region's supply resources with load centers. The major southern New England generation resources, as well as the supply provided via ties from northern New England, Hydro-Québec, and New York, primarily rely on the 345 kV transmission system for delivery of power to the area's load centers. This network provides significant bulk power supply to Massachusetts, Rhode Island, and Connecticut and is integral to the supply of the Vermont load in northwestern New England. The SNE area has experienced significant load growth, numerous resource changes, and changes in inter-area transfers.

The east–west transmission interface facilities divide New England roughly in half. Vermont, southwestern New Hampshire, western Massachusetts, and Connecticut are located to the west of this interface; while Maine, eastern New Hampshire, eastern Massachusetts, and Rhode Island are to the east. The primary east–west transmission links

[5] Source: *Needs Analysis* Figure 1-1.

are three 345 kV and two 230 kV transmission lines. A few underlying 115 kV facilities are also part of the interface; however, most run long distances, have relatively low thermal capacity, and do not add significantly to the transfer capability. In the early 1990s, this interface was important to monitor in day-to-day operations because of constraints in moving power from the significant generation in the west to Boston and its suburbs in the east. Following the influx of new generation in the east in the late 1990s, this interface now becomes constrained in the opposite direction, from east to west.

Supplying southern New England with electricity involves a number of complex and interrelated performance concerns. Connecticut's potential supply deficiencies, the addition of the Stoughton 345 kV station to serve the Boston area, and the demands of Rhode Island and western New England combine to significantly strain the existing 345 kV network. These challenges are compounded further by transmission constraints in the Springfield and Rhode Island areas under contingency conditions. The following transmission transfer capabilities are all interrelated:

- Southeastern Massachusetts (SEMA) export
- Greater Rhode Island export (mostly generation located in Massachusetts bordering on Rhode Island)
- Boston import
- Rhode Island import
- New England East–West interface
- Connecticut import
- Connecticut East–West interface
- Southwest Connecticut (SWCT) import

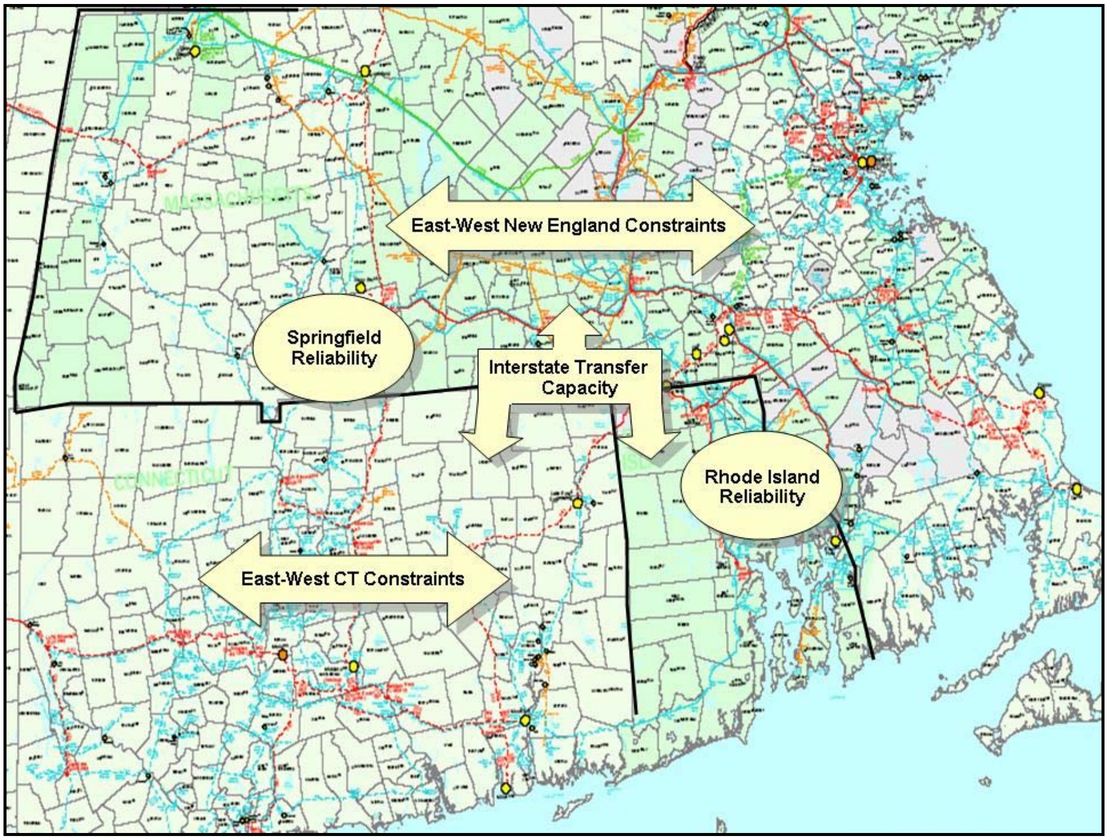
Transfers through these paths can contribute to heavy loadings on the same key transmission facilities.

These relationships exist for both thermal and stability limits. Studies have identified the relationship of stability limits among SEMA interface transfers, SEMA/RI exports, New England East–West transfers, New York–New England transfers, and the status of certain generators. Unacceptable torsional impacts on generators as a result of line reclosing also have become an issue in the SNE area. These behaviors illustrate the interdependent nature of the SNE 345 kV network. Recent analyses have quantified an additional interdependence between the ability to import power into Connecticut and the ability to supply load in the Springfield area. Springfield's reliability issues must be studied within the context of the overall southern New England analysis to not limit the benefits that improvements bring to the area and the ability to better integrate the supplies to the various load pockets in the region.

The existing transmission system does not allow for delivering surplus capacity to all load centers in southern New England. Regional east-west transfer limits and Connecticut power-transfer limitations do not allow this surplus capacity to be delivered to the load centers within Connecticut. The Springfield and Rhode Island areas have additional transmission reliability concerns, both thermal limitations and voltage violations, which lead to a set of interrelated concerns with respect to the reliability of transmission service across southern New England (see Figure 1-2).

(*Needs Analysis,* p. 1-3)

Figure 1-2: Southern New England Subareas and Constraints[6]



The problems illustrated in Figure 1-2 are described in the *Needs Analysis* as follows:

Statements of Need

Analyses performed for the 10-year period (from 2007 to 2016) showed that on the basis of ISO-NE planning procedures, the SNE transmission system over the 10-year study period has five major reliability concerns and a number of system deficiencies in transmission security, specifically area transmission requirements and transfer capabilities. These deficiencies form the justification for the needed transmission system improvements.

[6] Source: Needs Analysis Figure 1-2.

Reliability Concerns

The reliability concerns are as follows and are depicted in [Figure 1-2, above].

- **East–West New England Constraints:** Regional east–west power flows could be limited during summer peak periods across the SNE region as a result of thermal and voltage violations on area transmission facilities under contingency conditions.
- **Springfield Reliability:** The Springfield, Massachusetts, area could be exposed to significant thermal overloads and voltage problems under numerous contingencies at or near summer peak-load periods. The severity of these problems would increase as the transmission system attempts to move power into Connecticut from the rest of New England.
- **Interstate Transfer Capacity:** Transmission transfer capability into Connecticut and into Rhode Island during summer peak periods could be inadequate under existing generator availabilities for criteria contingency conditions.
- **East–West Connecticut Constraints:** East-to-west power flows in Connecticut could stress the existing system under "line-out," or N-1-1, contingency conditions (i.e., conditions under which a transmission element is unavailable and a single power system element is lost) during system peaks.
- **Rhode Island Reliability:** The system depends heavily on limited transmission lines or autotransformers to serve its peak-load needs, which could result in thermal overloads and voltage problems during contingency conditions.

Transmission Security Concerns

The *Needs Analysis* identified the following transmission security concerns related to meeting transfer capability and area transmission requirements:

Transfer Capability Concerns

- Power-transfer capabilities in the Connecticut area will not meet the area's import requirements as early as 2009. If improvements are not made by 2016, the import deficiency (outlined using a "load margin" approach in RSP06) for this area under conditions of generator unavailability and the loss of a single power system element (N-1 conditions) is expected to be greater than 1,500 MW assuming no new capacity is added.
- Based on planning assumptions concerning future generation additions and retirements within the Connecticut area, an import level of 3,600 MW for N-1 conditions and 2,400 MW for N-1-1 conditions will be needed by 2016.
- Connecticut currently has internal elements that can limit transfers from neighboring New England states under certain system conditions. These constraints limit the Connecticut east–west power transfers across the central part of Connecticut. The movement of power from east to west in conjunction with higher import levels to serve Connecticut overloads transmission facilities located within Connecticut that eventually tie into the new Middletown–Norwalk facilities.
- Under line-out (N-1-1) conditions and certain dispatch scenarios, the 345 kV transmission system in the southeastern Massachusetts and Rhode Island areas currently cannot support the requirements of southeast Massachusetts–Rhode Island, New England

east–west, and the Connecticut power transfers following a contingency. These interfaces all have simultaneous and interrelated power-transfer limits.

- Rhode Island and Springfield have insufficient import capability to meet their load margins through 2016.
- The flow of power through the Springfield 115 kV system into Connecticut increases when the major 345 kV tie line between western Massachusetts and Connecticut . . . is open because of either an unplanned or a planned outage. As a result, numerous overloads occur in the 2009 simulations. These overloads are exacerbated when Connecticut transfers increase.

Concerns about Area Transmission Requirements

- In the Springfield area, local double-circuit tower (DCT) outages, stuck-breaker outages, and single-element outages currently can result in severe thermal overloads and low-voltage conditions.
- The severity, number, and location of the Springfield overloads and low-voltage conditions highly depend on the area's generation dispatch. Additional load growth and unit outages in the Springfield area would significantly aggravate these problems. As a result, network constraints in the Springfield area limit the system's present ability to serve local load under contingency conditions.
- Thermal and voltage violations can occur on the existing Rhode Island transmission system, dependent on unit availability and transmission outages (planned or unplanned). Relatively high load growth in the southwestern area and the coastal communities in recent years have increased the possible occurrence of criteria violations.
- The capabilities of the underlying Rhode Island 115 kV system currently are insufficient to handle the power requirements within the state following the loss of 345 kV transmission facilities, both lines and autotransformers, under certain system conditions. For line-out conditions, the next critical contingency involving the loss of a 345/115 kV autotransformer or a second 345 kV line would result in numerous thermal and voltage violations."

Needs Analysis, Executive Summary, pages iii-v.

1.2.2 Development of the Options Analysis

Having identified the interrelated needs in the Southern New England Region, the working group turned to an analysis of transmission solutions – or "Options" - that would address those needs. This part of the coordinated planning effort continued through 2006 and 2007. Drafts of the *Options Analysis* were developed during this time and a final draft was posted for stakeholder comment on the ISO-NE website in April, 2008, with comments due by May 29, 2008. As described in the *Options Analysis:*

> The first step for this study was to establish the design objectives for the future southern New England transmission system based on the reliability deficiencies identified in the Needs Analysis. Using these design objectives, the working group developed and evaluated

a combination of complementary options for upgrading the system to meet the identified performance objectives during the long-term planning horizon.

In formulating each option, the working group considered more than just the performance of the option under specific conditions. It also considered the relationship that each option could have with other components of the comprehensive solution for the SNE region, with other elements of the transmission system, and with the regional transmission system as a whole. Consideration of these relationships ensured that the development of a "solution" was comprehensive and did not have an adverse impact on other parts of the bulk transmission system. These relationships led the working group to develop an approach to solving the SNE region's needs with these four components:

- **Interstate Reliability Component**—This component provides an additional link between Massachusetts, Rhode Island and Connecticut or, in one case, just between Rhode Island and Connecticut, and improves regional transfer capabilities. Initial brainstorming sessions among working group members resulted in 17 options for the Interstate Reliability component, of which five viable options remain.
- **Rhode Island Component**—This component increases Rhode Island's access to New England's 345 kV bulk transmission system and eliminates both thermal overloads and voltage violations. Three options (two Interstate Reliability options plus one independent option) were developed to better connect Rhode Island to the rest of the system, three options were developed to extend these new facilities farther into the major load center in southwest Rhode Island, and two options were developed to bring an additional source into the 115 kV load center from the east.
- **Connecticut East–West Component**—This component provides an additional link between western and eastern Connecticut and improves system transfer capabilities between these areas. Initially, four options were developed for this component. One option was eliminated as a result of poor performance, which left three options for further study.
- **Springfield Component—**This component eliminates both thermal and voltage violations in the Springfield area while increasing the area's access to the 345 kV bulk transmission system. The number of 345 kV options for the Springfield component was limited; however, 35 options were initially developed because a number of possible 115 kV solutions would work well with any of the 345 kV options, which created a multiplicative effect. Three 345 kV options remain, each having four 115 kV variations, for a total of 12 potential solutions.

> Developing the options for each of these four components has been an iterative process for the working group. Options that appeared to be capable of mitigating reliability concerns were formulated and then analyzed for compliance with design criteria and objectives. Additional modifications were formulated as necessary and then the option was reevaluated. This step was repeated until either the option was clearly workable or was determined to be unviable or not practical because it would require too many modifications.
>
> *Options Analysis*, p. 5

In the initial study sessions, 17 Interstate options were developed for discussion. Options identified as impractical, infeasible or likely poor performers were eliminated over time, and new options were added to the mix. *Options Analysis*, p. 10. Ultimately, five options were identified as meeting the basic performance requirements of the study for the Interstate component of NEEWS, strengthening the ties between the southern New England states, and increasing the ability to move power between eastern and western New England. These five options were briefly described as:

> - **Interstate Option A**—a new 345 kV line from the Millbury, MA, substation to the West Farnum, RI, substation and then to the Lake Road, CT, substation and terminate at the Card, CT, substation
> - **Interstate Option B**—a new 345 kV line from the West Farnum substation to the Kent County, RI, substation and then to the Montville, CT, substation. (The line from the West Farnum substation to the Kent County substation is part of the Rhode Island component.)
> - **Interstate Option C**—a new 345 kV line from the Millbury substation to the Carpenter Hill, MA, substation and terminate at the Manchester, CT, substation
> - **Interstate Option D**—a new 345 kV line from the Millbury substation to the Carpenter Hill substation to the Ludlow, MA, substation to the Agawam, MA, substation to the North Bloomfield, CT, substation. (The line from the Ludlow substation to the Agawam substation to the North Bloomfield substation is part of the Springfield component.)
> - **Interstate Option E—**a new 1,200 MW high-voltage direct-current (HVDC) tie between the Millbury substation and the Southington, CT, substation
>
> *Options Analysis*, p. 5

2.0 SELECTION OF A PREFERRED SOLUTION FROM THE FIVE INTERSTATE RELIABILITY OPTIONS IDENTIFIED IN THE *OPTIONS ANALYSIS*

The *Options Analysis* recognized that each of the five Interstate Reliability options that were considered potentially viable after the initial review had different system performance advantages and disadvantages, and concluded with an assignment to the TOs to further evaluate these characteristics and "to analyze the environmental, cost, constructability, and routing aspects of each option within each component" so that "selections can be made on the basis of all pertinent information." *Options Analysis*, p. 54. Pursuant to this mandate, the TOs critically examined each of the five Interstate Reliability options.

2.1 SUMMARY OF THE ANALYSIS OF THE FIVE INTERSTATE RELIABILITY OPTIONS

Although the *Options Analysis* determined that five electrical Options would meet a set of threshold system objectives, it also noted that each option "offers different advantages and disadvantages compared with the other options in terms of system performance." Accordingly, the TOs further analyzed the technical merits of each of the options, before developing cost, routing, and environmental information as needed to fairly compare them. Since the TOs identified two distinct routes for one of the electrical options, the total number of options evaluated became six. As a practical matter, winnowing down the options did not require the development of equally detailed routing and environmental information for all options. Where technical and/or cost analyses were sufficient to eliminate an option, a full environmental analysis was not required.

The TOs presented the preliminary results of their analysis of the options for all four components of NEEWS to the ISO-NE Planning Advisory Committee (PAC)[7] on December 15, 2006. With respect to the Interstate Reliability Component, the TOs identified Option A as "preferred to date, subject to PAC input." A copy of the presentation slide summarizing the basis of that preference is reproduced below.

[7] The Planning Advisory Committee, or PAC, is established under Section 2.1 of Attachment K and, under Section 2.2, is given broad roles to provide input and feedback to ISO-NE in the regional planning process, including the development and review of Needs Assessments and the conduct of Solution Studies.

Figure 2-1: Summary Comparison: Top Interstate Reliability Options[8]

Best — Worst

Top Interstate Options		Network Performance	Human Environment Considerations	Natural Environment Considerations	Delivery Timeframe	Planning Grade Estimate
Option A Millbury ⇔ Card Preferred to-date. Subject to PAC input.		Has the greatest combined system benefit of any of the options	Relatively low potential impact on developed areas	Relatively low potential for impacting protected lands and resources	Feasible to site and build by date of need	In the lowest cost range $400M (±25%)
Option B Kent County ⇔ Montville		Meets basic solution criteria but with operations issues	Moderate-to-high potential impact on developed areas	Low-to-moderate potential for impacting protected lands and resources	Low likelihood of timely delivery due to anticipated siting issues	In the higher cost range $450M (±25%)
Option C Millbury ⇔ Manchester	Route 1	Meets solution criteria and has many system benefits	Would require significant condemnations	Requires significant clearing for new ROW	Not feasible to site and build by date of need	Low basic estimate, with major uncertainty $400M (±25%)
	Route 2	Same as C-1 but involves a long line segment	Moderate potential impact on developed areas	Moderate potential for impacting protected lands and resources	Feasible to site and build by date of need	In the higher cost range $450M (±25%)
Option D Millbury ⇔ Ludlow		Meets basic solution criteria, but with the lowest operating limit of the options	Same as Option C-Route 2	Same as Option C-Route 2	Feasible to site and build by date of need	In the higher cost range $450M (±25%)
Option E HVDC: Millbury ⇔ Southington		Meets basic solution criteria but is not expandable, is less flexible and has higher system losses	Moderate potential impact on developed areas	Low-to-moderate potential for impacting protected lands and resources	Feasible to site and build by date of need	In a significantly higher cost range $1,300M (±25%) * (*Solves both the Interstate and CT E-W components, but is still very high when compared with the $600M total for the combined preferred)

[8] Source: TO's PAC Presentation 12/15/06 Slide.

Following the PAC meeting, the TOs continued to refine their evaluation of the options, concentrating in particular on developing current and more detailed cost estimates for each of them.[9] In addition, the TOs made a detailed comparative evaluation of the routing and environmental characteristics of the two most promising options; in particular, Options A and C-2. This additional work confirmed the tentative conclusion reported at the December, 2006 PAC meeting. See Appendix Item 3 of this report.

The following paragraph summarizes the reasoning by which the TOs selected Option A as the preferred Interstate Reliability solution.

The TOs first eliminated Option E – the HVDC solution - on grounds of inferior performance and high cost. (*See,* § 2.2) They then went on to comparatively evaluate the four AC options. The TOs had already done considerable work on a project very similar to that identified as Option A in the *Options Analysis*, and so were able to quickly determine that it merited further serious consideration, and should be kept "on the table." (*See,* §2.3) Option B was eliminated for inferior performance and high cost (*See,* § 2.4); and Option D was determined to be impractical in the form envisioned in the *Options Analysis,* and virtually indistinguishable from one of the variants of Option C when modified to be constructible. (*See*, § 2.7) Two potential routes for Option C were examined. (*See,* §2.5) One route (designated as Option C-1, which would have been in large part on new right-of-way adjacent to an interstate highway corridor) was found to be impractical and costly. (*See,* § 2.6) The other route (Option C-2) was evaluated in detail. (*See,* § 2.8, app. 4) Ultimately, a comparative analysis of Option A and Option C-2 showed that, although both potential solutions had merit, Option A performed better, cost less, and had fewer environmental and social impacts. (*See,* §2.7) Accordingly, Option A was selected as the preferred transmission solution.

The following sections describe this evaluation in detail.

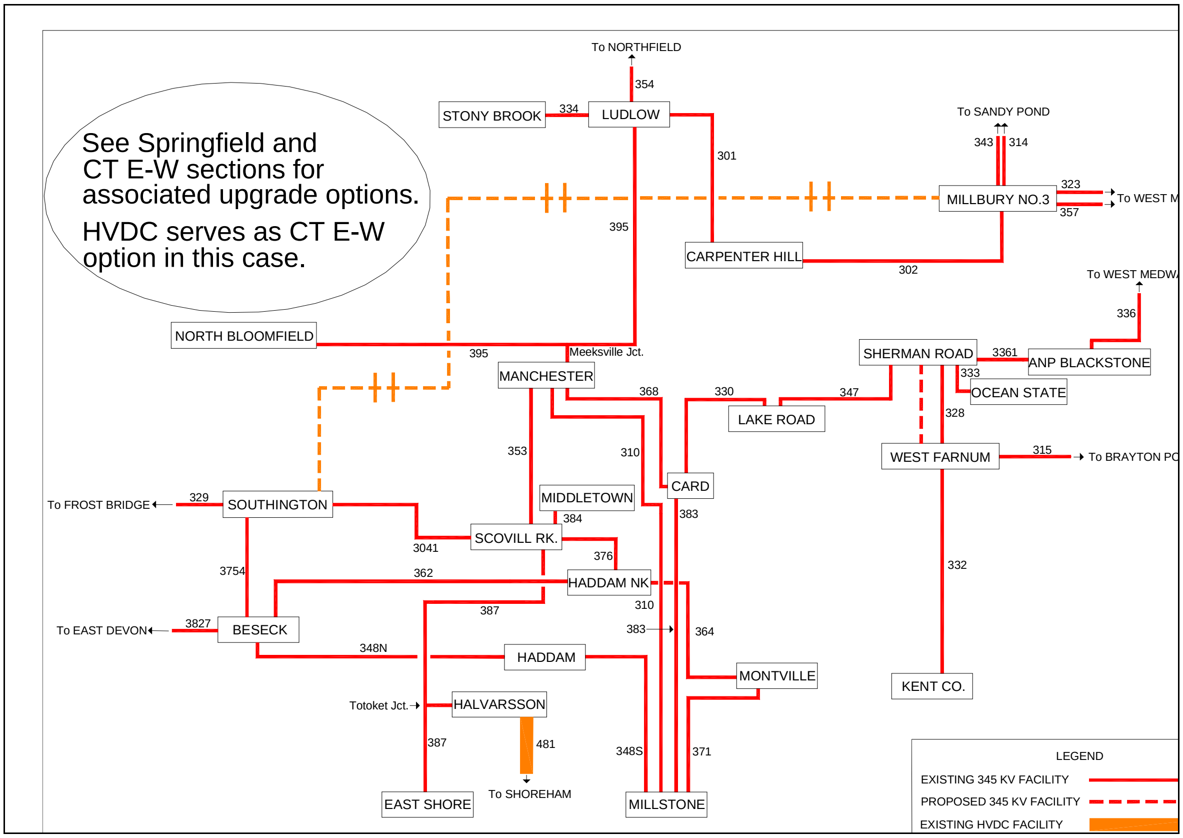
2.2 EVALUATION OF HVDC TECHNOLOGY (OPTION E)

As described in the *Options Analysis*, Option E would be a 1,200 MW HVDC line that would be constructed from National Grid's Millbury Switching Station to CL&P's Southington Substation (an

[9] In the years since ISO and the TOs first identified a need for a Card/Sherman or West Farnum/Millbury 345-kV line, transmission line commodity and labor costs have risen substantially. The most recent cost estimates for all of the options are summarized in a spreadsheet attached as Item 1 in the Appendix to this report, which sets forth the current estimated "all in" costs of each of the options (including siting and permitting, labor and materials, owners' direct costs, overhead, and contingencies) ("Cost Spreadsheet").

approximate distance of 87 miles.) The major elements of this Option were depicted in the *Options Analysis* by the following one-line diagram:

Figure 2-1: Option E[10]



This Option would serve as an alternative to both the Interstate Reliability and Central Connecticut components of NEEWS, and so must be compared to combinations of those AC Improvements. Option E was the first Option to be eliminated because it offered fewer system benefits than most AC Options at a greater cost.

2.2.1 Evaluation of Option E in the Options Analysis

The draft *Options Analysis* showed no dramatic performance advantage of an HVDC over a conventional AC solution. The *Options Analysis* summarized some of the important performance characteristics of each of the options in tabular form. The summary table for Option E *(*at p. 23) set forth the following selected "performance factors."

[10] Source: *Options Analysis* Figure 4-5.

Table 2-1: System Performance Factors of Interstate Option E[11]

System Performance Factors	Results	Comments[(a)]
Effect on transfer capability between New York and New England	This option was originally more limiting on NY to NE. However, the 2010 western MA improvements eliminate that limiting condition.	See Section 4.3.8 [of *Options Analysis*] for details
Improving New England east–west transfer capability	Increases capability by 1,580 MW (to 4,378 MW total)	Ranked second
Improving Connecticut's import capability	N-1 import capability increases by 1,974 MW (to 4,651 total); N-1-1 import capability increases by 1,621 MW (to 2,813 MW)	N-1 limit ranked first among the options; N-1-1 ranked first
Eliminating high line loadings under contingencies (2016)	100 high line loadings total; 18 high all-lines-in loading; 82 high line-out loadings	Ranked fourth
Improving system voltages during contingencies (2016)	23 borderline voltage cases following N-1 contingencies	Ranked fourth
Decreasing system losses	68/33 MW (conventional DC/DC light) reduction in system losses compared with pre-project system	Ranked second/fifth
Decreasing short-circuit duty	7.5% increase on worst location	Ranked first
Improving system expandability	No	DC system not easily expandable; an additional converter station would be needed for adding a generator or substation

(a) The performance rankings range from one to five, one being the best and five being the worst.

Option E's first ranking in decreasing short circuit duty provided no reason to select it. As the *Options Analysis* noted: "The differences in these results…do not appear to be significant and may not be a material factor for selecting a preferred alternative." (*I*d., p.27)

Thus, the only factor that caused Option E to stand out in a positive light from the AC options was its top ranking in the transfer capability categories. However, the incremental capability provided by Option E is modest. Although Option E comfortably exceeds the "targets" for increasing Connecticut's import capacity (923 MW for N-1 and 1,308 MW for N-1-1 capability) several of the AC options did as well. For instance, Option A provides an N-1 capability improvement of 1,766 MW - nearly double that of the target. While Option E provides a further increment of N-1 import capability of 208 MW (about 12%

[11] Source: *Options Analysis* Table 4-6

more than Option A) its advantage over Option A with respect to N-1-1 import capability is only 30 MW, or less than 2%. In terms of a planning horizon of 10 or 20 years, these are very similar improvements.

On the other hand, Table 4-6 of the *Options Analysis* notes: "DC system not easily expandable." The *Options Analysis* explains this limitation further in section 4.3.8, as follows:

> In terms of future system expandability and system flexibility, all four AC options offer much more expandability than the DC option. DC systems historically have been used for relatively long, point-to-point type delivery and have not been integrated into the center of AC systems.
>
> The only action required to increase the capacity of an AC line might be a simple reconductoring; increasing the capacity of a DC system would require, at a minimum, either major converter additions or converter change-outs at each end of the line. Adding a new generator midpoint to a DC line would most likely require a new converter station, possibly with two new converters. Similarly, the need to connect to a lower voltage system, either to provide voltage support or eliminate thermal overloads, would be equally difficult.
>
> *Options Analysis*, §4.3.8

The expandability and flexibility limitations of Option E noted in the *Options Analysis* have many significant and undesirable system consequences. In particular:

- The requirement of building "major converter additions or converter change-outs" at each end of the line in order to expand the capacity of the line in the future is a major inhibition of the development the transmission system to respond to changing load patterns and load growth. Expanding the capacity of an HVDC line is equally problematic. As a practical matter, in designing an HVDC system the best way to provide for future growth needs is to build in overcapacity when the system is constructed, thus exacerbating the highly unfavorable cost comparison between AC and HVDC systems.
- The requirement of adding one or perhaps two new converter stations in order to add a new generator to the line would pose technical and economic obstacles that would certainly discourage, and probably prevent, the development of any new generation along the path of the line, and thus interfere with the development of a competitive generation market.
    - *Technical Obstacles to Adding Generation*

      Adding additional terminals to an HVDC system greatly complicates the system design and control coordination. Therefore, almost all HVDC systems have been constructed as two-terminal systems. A very few HVDC lines have been constructed with more than two terminals, such as the Hydro Québec – New England line. In the case of that line, however, the current operating practice is to utilize the system with only two terminals operating at any given time. No generation owner would want to accept a risk of not being able to operate when needed because all three terminals of the line could not be in operation simultaneously.

  - *Economic Obstacles to Adding Generation*

    Generation developers must pay the cost of interconnecting a generating plant to the existing transmission system. Usually, these costs entail the construction of a relatively short AC line and a substation. The cost of building one or two new DC converter station in order to interconnect with the AC system would be many multiples of the cost of a simple AC interconnection.

- The limitations and difficulties noted in the *Options Analysis* of connecting a DC line "to a lower voltage system, either to provide voltage support or eliminate thermal overloads" is another major disadvantage of HVDC technology for the contemplated application 345-kV AC transmission systems can be easily tapped to support the 115-kV network by the use of 345-kV/115-kV autotransformers, as CL&P has recently done at the Barbour Hill, Killingly, and Haddam Substations. If this option were not available, CL&P would have had to make extensive improvements to its 115-kV system, at greater cost and with more environmental impacts.

2.2.2 Further Evaluation of Option E

After the first draft of the *Options Analysis* was issued, the TOs further evaluated an HVDC alternative, with the assistance of GE Energy. To memorialize this work, GE prepared a report, which is included in Appendix Item 2 of this Report. *See,* Appendix Item 2, GE Energy, *Applicability of an HVDC Option in the NEEWS Upgrade*, d. July 2008 ("GE Report"). In addition, the TO's evaluated the costs of a hypothetical HVDC line from Millbury to Southington, as contemplated in Option E. The results of these analyses are summarized in the following sections.

2.2.2.1 Technical Assessment of Interstate Reliability Option E

The GE Report summarizes the technical attributes of HVDC technology that would have a negative impact if applied to the NEEWS project as follows:

> These include increased line terminal space requirements, converter station losses, lack of inherent power flow response to mitigate system contingencies, reduced short-term overload capability, risk of sub-synchronous torsional interaction with generating units, constrained future system expandability, aggravating system resonance issues, and reduced line reliability.
>
> HVDC also has a great amount of complexity, which must be carefully managed during system specification, design, commissioning, and during any future system upgrades. Failure to adequately manage the complexities of system interactions can pose a further risk to system security and reliability.
>
> *GE Report,* Section 7, p. 31

The GE Report concludes:

> The proposed HVDC line forming Option E of the New England East-West Solution is dissimilar to any established HVDC application niche. Weighing the very limited technical advantages of HVDC transmission technology for the NEEWS project application, against the significant technical disadvantages, there is no justification for favoring an HVDC solution over an ac solution unless the HVDC solution is substantially less costly. Costs are not within the scope of this paper, but it is reasonable to estimate that performing the solution with HVDC will, in fact, be much more costly than with ac transmission lines.
>
> *GE Report,* Section 7, pp. 31, 32

2.2.2.2 HVDC Option Cost and Conclusion

HVDC lines are used for relatively long point-to-point energy delivery but, as noted in the *Options Analysis*, "have not been integrated into the center of AC systems." *Options Analysis*, Section 4.2.1. Whether an HVDC option was constructed overhead or underground, it would require converter terminals at each end to connect the line into the existing AC transmission system. Preliminary estimates for the converter terminals for Option E indicate that those components alone, without the overhead or underground lines, or other required AC system modifications, would cost approximately $536 million. Factoring in the route of at least 85 miles of overhead or underground line that would need to be constructed between converter terminals, the total cost of Option E would be much higher than the total estimated cost of $773 million for Interstate Reliability Option A and the Central Connecticut Option C, which the HVDC Option E would replace.

Given this cost comparison, the TOs decided to eliminate the HVDC option without development of a detailed estimate of either an overhead or underground HVDC line. Inclusion of HVDC line costs would only serve to greatly increase the cost differential between the HVDC options and the lower cost AC options.

Based on the complexity of the HVDC option, the higher cost, the difficulty of integrating it into the AC system, the operating issues and the lack of expandability of an HVDC option, Option E was eliminated.

2.3 EVALUATION OF THE AC OPTIONS

After the elimination of Option E, evaluation of the AC options was straightforward. Option A was re-evaluated, determined to be a likely first choice, and "kept on the table" for further evaluation. Two options – B and D – were found to be inferior to the others and were eliminated. Of the two routes identified for Option C, one turned out to be impractical and significantly more costly than Option A. Closer analysis comparing Option C using the remaining route with Option A was required before confirming the choice of Option A.

2.3.1 Evaluation of Interstate Reliability Option A

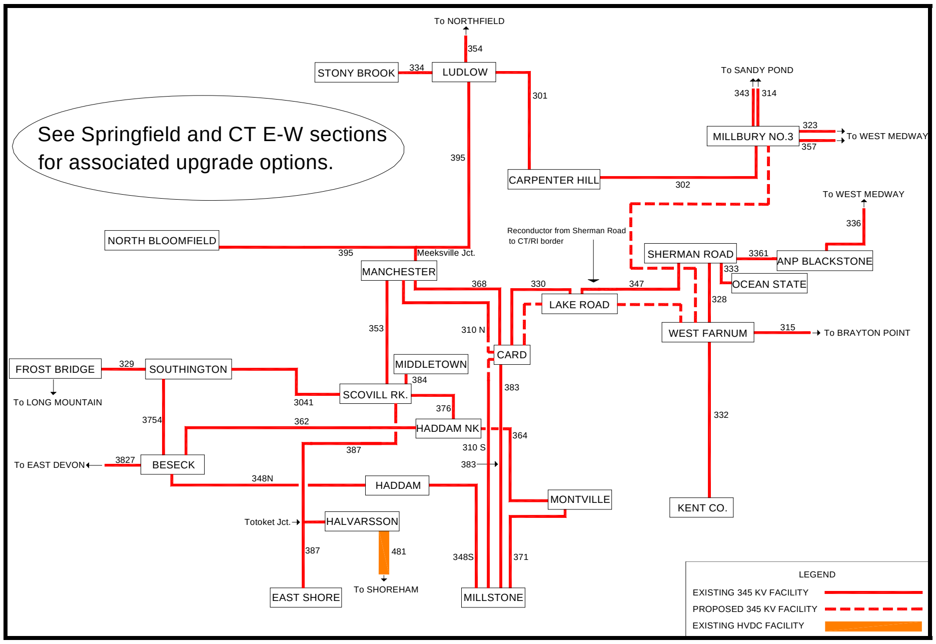
As the first step in a comparative evaluation of the AC Interstate Reliability options, the TOs confirmed that Interstate Reliability Option A, which had already been under consideration by the TOs at the time that the expanded regional planning effort began was a technically, environmentally, and economically practical solution for the need that the Interstate Reliability Component was required to address.

Section 4.2.2 of the *Options Analysis* described Option A as follows:

> This option adds a new 345 kV line that connects Millbury to West Farnum and then continues on to connect West Farnum to Card, with an intermediate connection at Lake Road. The reconductoring of the portion of the Sherman Road to Lake Road 345 kV line that physically is in Rhode Island also is part of this option.
>
> (*Options Analysis*, p.12)

The following one-line diagram in the *Options Analysis* depicts the major upgrades that comprise Interstate Option A.

Figure 2-2: Interstate Reliability Option A[12]



The geographic location of these upgrades is illustrated by the following Figure:

Figure 2-3: Interstate Reliability Option A – Route

12 Source: *Options Analysis* Figure 4-1.

2.3.1.1 System Benefits of Interstate Reliability Option A

Option A comfortably exceeded the principal numerical design criteria or "targets" of the study, which concerned the improvement of the CT import capability, as shown by the following excerpts from tables included in the *Options Analysis*, at p. 24 and 25:

Table 2-2: Connecticut 2012 N-1 Import Comparison[13]

Interstate Option	CT Import: N-1 (MW)	Incremental Improvement in CT Import: N-1 (MW)
Base	2,677	
Target[(a)]	3,574	923
A	4,443	1,766

(a) The target of 3,574 MW is the result of adding the year 2012 N-1 shortage of 1,074 MW (from Table 9-3 in RSP06) to the existing N-1 limit of 2,500 MW.

Table 2-3: Connecticut 2012 N-1-1 Import Comparison[14]

Interstate Option	CT Import: N-1-1 (MW)	Incremental Improvement in CT Import: N-1-1 (MW)
Base	1,192	
Target[(a)]	2,374	1,308
A	2,783	1,591

(a) The target of 2,374 MW is the result of adding the year 2012 N-1-1 shortage of 1,154 MW (from table 9-3 in RSP06) to the existing N-1-1 limit of 1,220 MW.

Moreover, the performance of Option A in comparison to the other AC options was very good. Option A was first or second in most categories, and very close to the leader in all categories in which it was not the leader. This comparative performance is evident from the following revised version of Table 4.7 in the *Options Analysis* (at p. 27), which substitutes a comment column for the original Option E column.

[13] Source: *Options Analysis* Table 4-9.
[14] Source: *Options Analysis* Table 4-10.

Table 2-4: Comparison of AC Interstate Options[15]

Interstate Options and Needs	Pre-Project System	Option A	Option B	Option C	Option D	Comment re: Option A
New England east–west transfer capability (MW)	2,798	4,174	3,996	4,091	4,651	2nd to Option D
CT import: N-1 (MW)	2,677	4,443	3,975	4,443	4,580	Tied for 1st w Option C D*
CT import: N-1-1 (MW)	1,192	2,783	2,539	2,727	2,454	1st
Number of 'high' 'all-lines-in' loadings in 2016	NA	3	21	6	5	1st
Number of 'high' 'line-out' loadings in 2016	NA	43	97	67	71	1st
Total high loadings	NA	46	118	73	76	1st
Number of borderline voltage cases	NA	6	29	8	9	1st
Decrease in New England system losses (MW)	NA	56	55	69	57	3rd; but only 1MW compared to Option D (2nd)
Short-circuit impact (percent increase)	NA	8.9	5.3	9.3	7.5	3rd but difference "not significant" §4.3.7

* After elimination of Option D as a distinct alternative (*see* §2.3.4 of this report) Option A is tied for 1st in this category with Option C.

15 Source: *Options Analysis* Table 4.7.

In addition to the system benefits summarized in the table reproduced above, the final *Options Analysis* pointed out benefits that had been identified by a stability screening analysis and by input from operations personnel. The stability screening results were summarized in Section 4.3.6 of the *Options Analysis* as follows:

> If the West Medway South bus were out of service, only Option A would be able to mitigate system instability for a three-phase fault on West Medway bus B (stuck breaker 104). Similarly, only Option A would prevent a Lake Road trip if the 330 line (Lake Road–Card 345 kV) were out of service and the 347 line (Sherman Road–Killingly 345 kV) had a fault. This also would hold true if the fault were on the 330 line and the 347 line were out of service. Also under Option A, Lake Road would not trip if the 347 line were out of service and the 383 line (Millstone-Card 345 kV) at Card had a three-phase fault that resulted in a 3T stuck-breaker condition (the 383 line, the 330 line, and the autotransformer)
>
> *Options Analysis*, p. 27

The input from operations personnel provided further support for the choice of Option A. The *Options Analysis* summarized this input in Section 4.2.1 as follows:

> The working group presented the details of the Interstate options to operations personnel from ISO New England, CONVEX, and REMVEC at a joint Planning-Operations meeting. The operators, who were not presented with any information concerning cost, environmental, or routing impacts, preferred Option A for the following reasons:
>
> - It best alleviates the angular difference between Rhode Island and Connecticut, thus removing all the operating complexities related to taking lines out of service in the area.
> - Alleviating the angular differences will eliminate the need for the SPS that takes the Lake Road units out of service for certain contingencies to avoid possible shaft damage.
> - The new Killingly substation serving eastern Connecticut can receive support from the rest of New England even with the 347 line out of service.
>
> *Options Analysis*, p. 29

Finally, the TOs recognized that Option A offered the following system benefits, which were in part responsible for the initial attention this Option had received prior to the expansion of the planning process:

- It reinforces the electrical connection between Massachusetts and Rhode Island and between Connecticut and Rhode Island for the benefit of all, providing each with access to competitive power markets and potential access to renewable energy sources.

- It improves access to newer more efficient generation resources in southeastern Massachusetts – an area known to have excess generation.
- By extending to Millbury, it creates a platform for accessing lower cost, low-emission, and renewable generation sources in Northern New England and Canada.
- It also provides access to the natural gas pipeline paths in northeastern Connecticut, northern Rhode Island and southern Massachusetts, near which future generation is most likely to develop.
- It establishes a new supply source to Rhode Island, thereby increasing the reliability of the Rhode Island system.
- It establishes a 345-kV loop around several large generators in central Massachusetts, by connecting National Grid's Millbury Switching Station with their West Farnum and West Medway Substations.
- By providing a second 345-kV source to the Lake Road Substation, Option A should make all units at Lake Road Generating Station in Killingly eligible to be considered as fulfilling Connecticut's local sourcing requirement. (The Local Sourcing Requirement is a measure of resource adequacy. It is the minimum amount of capacity that must be located within an import-constrained load zone to meet the system wide loss of load expectation of one day in 10 years.)

2.3.1.2 Preliminary Routing/Environmental Impact Evaluation Of Interstate Reliability Option A

By the time that the *Options Analysis* was first issued in draft, in February of 2007, the TOs had already gathered extensive routing and environmental information concerning Interstate Reliability Option A. The initial routing analysis had indicated that all but approximately 1.5 miles of the 76.3 miles of a new 345-kV line could be accommodated within existing rights-of-way (ROWs) that generally traversed sparsely settled or undeveloped areas. It also indicated that the ROWs are presently wide enough to allow the development of the 345-kV line using steel-pole or laminated wood-pole H-frame structures that would be similar in appearance to the existing 345-kV lines that occupy the same rights-of-way. The 1.5 miles where the right-of-way width was insufficient to accommodate a new line consist of two locations, the Mansfield Hollow Reservoir property and Mansfield Hollow State Park. Much of the new ROW needed is across land owned by the U.S. Army Corps of Engineers (USACE) and leased by the USACE to the Connecticut Department of Environmental Protection (CTDEP). CL&P would require a voluntary conveyance of additional easement rights from the USACE, with the consent of the CTDEP.[16]. While a

[16] Later on, when more detailed engineering design of the 1-mile-long loop of the existing 345-kV line (circuit 310) into the Card Street Substation in Lebanon was performed, it became apparent that additional right-of-way in the

lack of cooperation by the agencies could have required substantial reconfiguration of Option A through this small area, contacts with the agencies have been encouraging to CL&P.

Finally, the Option A route appeared promising in that it could be constructed entirely or nearly entirely overhead, consistently with the provisions of section 16-50(p)(i) of the Connecticut General Statutes, which establishes a rebuttable presumption that electric transmission lines at 345 kV and above shall be constructed underground where they are "adjacent to" certain land uses, described as: "residential areas, private or public schools, licensed child day-care facilities, licensed youth camps [and] public playgrounds." The existing right-of-way did not traverse any public playgrounds or licensed youth camps; and it appeared that the groups of houses along the right-of-way were not densely developed and integrated "neighborhoods" that would probably be considered to be "residential areas" within the meaning of the statute. There were a few licensed daycares and one private school adjacent to the right of way, but it seemed likely that other line designs could be employed in these areas, consistent with the Council's EMF Best Management Practices for the Construction of Electric Transmission Lines in Connecticut, or that, in any case, the underground "presumption" would be overcome by a showing that the cost of underground alternatives was unreasonable.

Accordingly, the preliminary routing and environmental analysis was sufficiently promising to keep Option A under active consideration. A more detailed analysis of the Option A routing, comparing it to that of Option C-2, is set forth in Appendix Item 3 of this report.

2.3.1.3 Estimated Cost of Interstate Reliability Option A

As reported at the December 15, 2006 PAC meeting, preliminary "planning grade" estimates of the Interstate options identified Option A in the lower cost range. Later, more detailed cost estimates reflecting escalating labor and material costs showed Option A to be the least costly Interstate Reliability Option, with a "fully loaded" cost of approximately $460 million, assuming all-overhead line construction. *See*, Cost Spreadsheet, Appendix Item 1.

2.3.1.4 Conclusion of Preliminary Reevaluation of Option A

Since Option A appeared to offer a good combination of system benefits, it could be routed as an all-overhead, or nearly all-overhead line with minimal environmental impacts, and it appeared to be an

immediate area of that substation would be required. This tie, and the additional ROW it will require, came common of all the AC Options.

economical solution, it was recognized as a likely preferred option and kept "on the table" while the other AC options were further investigated.

2.3.2 Evaluation of Interstate Reliability Option B

As described in the *Options Analysis*, Interstate Reliability Option B would extend the existing 345-kV line from the West Farnum Substation to the Kent County Substation into Connecticut to Montville Substation, providing a common supply path for both Rhode Island and Connecticut. This option would also include the reconductoring of the 345-kV line from Millbury through Carpenter Hill to Ludlow and the 345-kV line from ANP Blackstone (MA) to Sherman Road. This option would not eliminate the need for the second 345 kV line between West Farnum and Kent County Substations which is proposed as part of the Rhode Island Reliability component of NEEWS. A one-line diagram of Interstate Reliability Option B is provided at page 17 of the *Options Analysis*.

Figure 2-4: Interstate Reliability Option B[17]

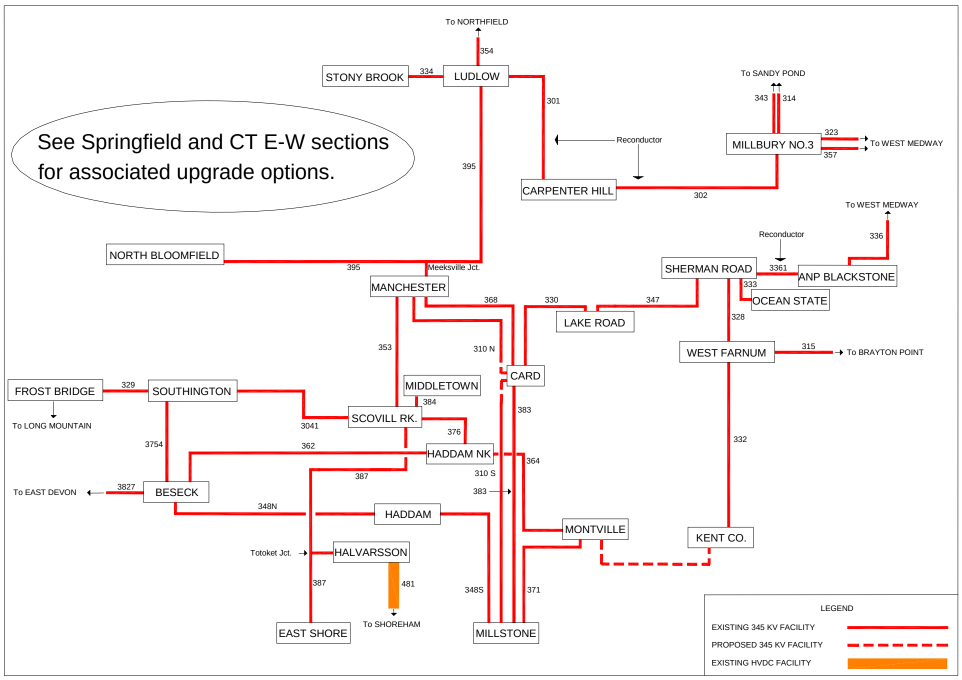


Figure 2-7 below illustrates the geographic location of the Option B improvements. The solid blue line indicates a new 345-kV line; the broken blue lines indicate reconductoring or rebuilding of existing 345-kV lines; and the purple line indicates reconductoring or rebuilding of 115-kV lines.

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[17] Source: *Options Analysis* Figure 4-2.

Figure 2-5: Interstate Reliability Option B – Route

2.3.2.1 Evaluation of Option B in the *Options Analysis*

The performance characteristics of Option B are summarized in of the *Options Analysis*, as follows:

Table 2-5: System Performance Factors of Interstate Option B[18]

System Performance Factors	Results	Comments[(a)]
Effect on transfer capability between New York and New England	Positive effect	See Section 4.3.8 [of *Options Analysis*] for details
Improving New England east–west transfer capability	Increases capability by 1,198 MW (to 3,996 MW total)	Ranked fifth
Improving Connecticut's import capability	N-1 import capability increases by 1,298 MW (to 3,975 total); N-1-1 import capability increases by 1,347 MW (to 2,539 MW)	N-1 limit ranked fifth among the options; N-1-1 ranked fourth
Eliminating high line loadings under contingencies (2016)	118 high line loadings total; 21 high all-lines-in loading; 97 high line-out loadings	Ranked fifth—highest number of high loadings
Improving system voltages during contingencies (2016)	29 borderline voltage cases following N-1 contingencies	Ranked fifth—highest number of borderline voltage issues
Decreasing system losses	55 MW reduction in system losses compared with pre-project system	Ranked fifth
Decreasing short-circuit duty	5.3% increase on worst location	Ranked second
Improving system expandability	Yes	AC lines can readily be tapped for future substations and generator interconnections.

(a) The performance rankings range from one to five, one being the best and five being the worst.

The above table demonstrates that Option B ranked behind all of the other AC options selected for further study in all ranked categories, except for "decreasing short circuit duty." As previously noted, the *Options Analysis* recognized that "the differences in these results…do not appear to be significant and may not be a material factor for selecting a preferred alternative." (*I*d., p. 27)

2.3.2.2 Further Assessment of the System Benefits of Interstate Reliability Option B

The TOs considered whether Option B offered significant system benefits not recognized in the above table, and concluded that it did not. This Option does offer one potential advantage over the other AC options in that it would provide a second Connecticut-Rhode Island connection at 345-kV on a different right-of-way than the existing 345-kV connection; the separation avoids the potential loss of both lines for an extreme contingency event occurring on one right-of-way. However, west of Montville Substation,

[18] Source: *Options Analysis* Table 4.3

Option B would place the new path for Connecticut imports on the same rights-of-way that are used by the multiple 345-kV lines from the Millstone Nuclear Power station and the Montville Generating station, which is an offsetting disadvantage for an extreme contingency on one right-of-way.

The Option B path south from West Farnum Substation, and then crossing into the southeast corner of Connecticut would also take it away from the natural gas pipeline paths in northeastern Connecticut, northern Rhode Island and south-central Massachusetts, near which future gas-fired generation is most likely to develop. The locations of the other AC options provide better access for future generators located along the gas-pipeline path.

2.3.2.3 Estimated Cost of Interstate Reliability Option B

Option B was recognized in the December 15, 2006 PAC presentation as being in the "higher cost range." (Slide 49). Further analysis has shown that it has the highest cost of all of the AC options, estimated at approximately $629 million (as opposed to, for instance, approximately $460 million for Option A. See, Interstate Reliability Options Cost Spreadsheet, Appendix Item 1. The reasons for this higher cost are:

- Although Option B requires the shortest new 345-kV line construction (51 miles) of the AC options, it requires the most reconductoring and rebuilding of existing 345-kV lines on other rights-of-way – more than 57.3 miles.
- Option B requires new construction and rebuilding/reconductoring on the most miles of right-of-way, whether 345-kV line work only is considered, or both 345-kV and 115-kV line work.
- Between Kent County Substation in Warwick, RI and Ledyard Junction in Ledyard, CT, a distance of 47.2 miles, approximately half of the existing 115-kV transmission line structures and conductors would need to be replaced in new locations to make room within the existing right-of-way for a new 345-kV line. Some distribution lines must also be relocated or underbuilt on nearby existing or proposed transmission line structures. The new 345-kV line would have to cross over existing 115-kV lines three times.
- Between Ledyard and Montville Substation (a distance of 3.77 miles), 1.15 miles of 69-kV underground construction would be required to make room on the ROW for the proposed 345-kV line. This includes crossing the Thames River. The existing overhead line structures on the remaining 2.75 miles of this right-of-way must be reconfigured in order to make room for the proposed 345-kV line.

2.3.2.4 Environmental/Routing Considerations Of Interstate Reliability Option B

Finally, the TOs considered whether Option B offered significant environmental or social advantages that could potentially offset the combination of fewest system benefits and highest cost. This Option affects the most ROW of any of the AC options. In addition, the route of the new 345-kV line crosses more environmentally sensitive areas than any of the other options, as indicated by the following description:

The Option B route, from west to east, would start at the Montville Substation, cross Horton Cove and then the Thames River, within the Connecticut coastal boundary. This initial 3.8-mile route segment would also traverse various wetlands associated with Pine Swamp in Ledyard, before terminating at Ledyard Junction, in Ledyard, Connecticut. From there to Kent County Substation in Rhode Island, a distance of 47.2 miles, the new 345-kV line would be aligned through a variety of water resources, including areas within both the Connecticut and Rhode Island coastal boundary. The principal water bodies traversed in Connecticut would include the Morgan Pond Reservoir (Ledyard); the Mystic River (Groton/Stonington); and the Pawcatuck River, which forms the boundary between Connecticut and Rhode Island.

The portion of the route in Rhode Island would traverse the Pawcatuck River again in Westerly, Pasquiset Brook (Charlestown), the Pawcatuck River again n Charlestown, and Chickasheen Brook (South Kingston). In addition, Option B would cross extensive wetland areas, including Indian Cedar Swamp Management Area and Great Swamp Wildlife Reservation (Charlestown), as well as wetlands associated with the Black Swamp in North Kingstown. Portions of the Option B alignment also would be within areas included as part of Special Area Management Plans (SAMPs), prepared pursuant to the regulations of the Rhode Island Coastal Resources Management Council (RICRMC). The RICRMC, which is authorized under the federal Coastal Zone Management Act to develop and implement coastal plans, has approved SAMPs for both the Pawcatuck River and Greenwich Bay areas.

Finally, the route also would traverse designated Narragansett Tribal Lands in Charlestown on the existing ROW.

2.3.2.5 Conclusion of Evaluation of Option B

Because Option B offered the fewest system benefits, was the most expensive AC Option, and offered no environmental advantage over the other AC options, it was eliminated from further consideration.

2.3.3 Evaluation of Interstate Reliability Option C

The *Options Analysis*, which focused on electrical connections rather than specific routes, identified a single Interstate Reliability Option C, which it described as:

> Interstate Option C provides a new 345 kV line from Millbury through Carpenter Hill to Manchester. In addition, a new 345 kV line from Sherman Road to West Farnum is required.
>
> *Options Analysis*, p. 16

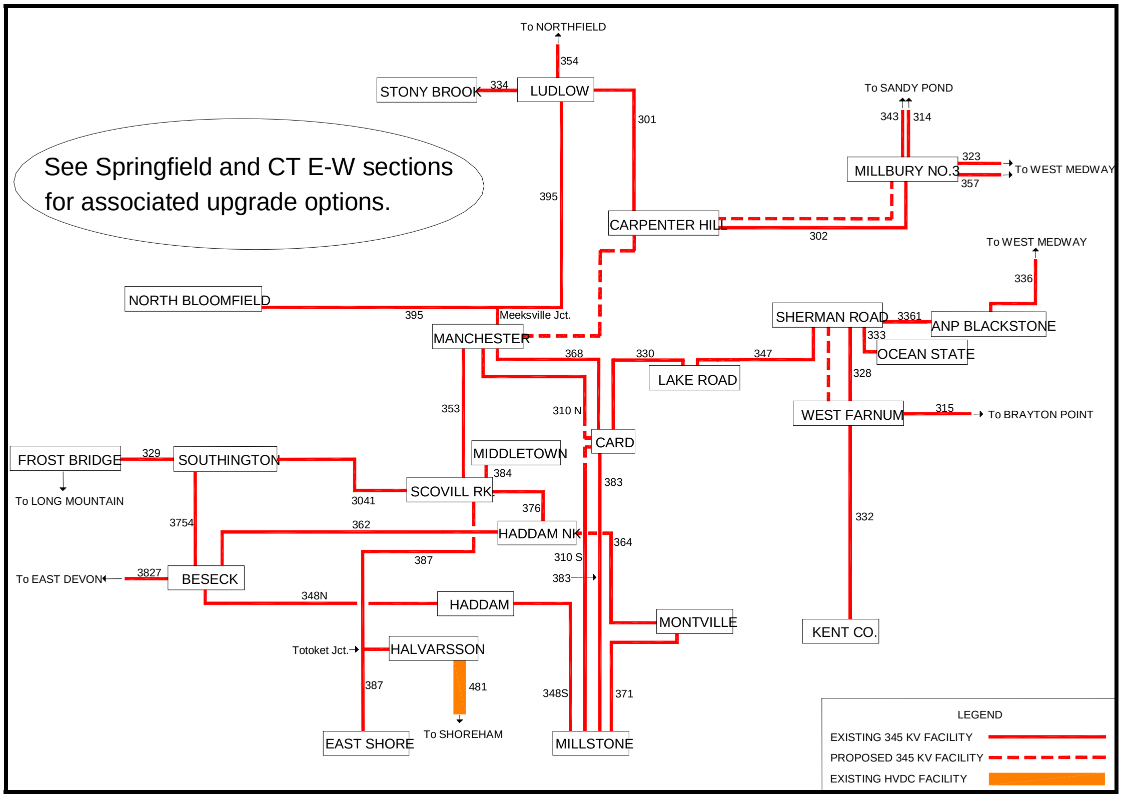
As discussed in the following sections, the Millbury to Carpenter Hill to Manchester portion of the option was evaluated assuming two different routes, and the variants of this Option incorporating each of these different routes were designated Options C-1 and C-2.

In addition to the Millbury to Carpenter Hill to Manchester 345-kV line, Option C includes a 9-mile 345-kV line between National Grid's Sherman Road Substation in Burrillville, Rhode Island and its West Farnum Substation in North Smithfield, Rhode Island. The route for these lines is the same for both Options C-1 and C-2.

The reconductoring of 6.6 miles of 115-kV line between National Grid's Little Rest Substation in Warren, MA and its Palmer Substation in Palmer, MA is also common to both Options C-1 and C-2.

The following one-line diagram showing the major improvements of Option C was provided as Figure 4.3 in the *Options Analysis:*

Figure 2-6 Interstate Reliability Option C[19]



However, to fairly evaluate the construction cost and scope implications of choosing Interstate Option C, an element shown on this diagram, but not listed in the *Options Analysis* as a component of Interstate Option C must also be considered. As explained in Section 5.3.3 of the *Options Analysis:*

> A new 345 kV line into Rhode Island is needed to respond to the contingency condition when both line 328 (from West Farnum to Sherman Road) and line 315 (from Brayton Point to West Farnum) are out of service. In the case of Interstate Options C, D, and E, this second-contingency condition would leave all of Rhode Island without a 345 kV connection and could result in very low voltages or voltage collapse for certain dispatch scenarios.
>
> For Interstate Option A (Lake Road to West Farnum and Millbury to West Farnum) and Interstate Option B (Montville to Kent County), this new 345 kV line segment from Sherman Road to West Farnum is not needed because Rhode Island second-contingency support is afforded by the Interstate Options themselves.
>
> *Options Analysis*, p.33

[19] Source: *Options Analysis* Figure 4.3.

Accordingly, while a new West Farnum to Sherman Road 345-kV line is listed in the *Options Analysis* as a component of the Rhode Island Reliability Project, its cost should be considered as a consequence of choosing Interstate Option C, D, or E over Options A or B – at least when comparing the respective costs of the Interstate Reliability components of NEEWS. For this reason, the attached Cost Spreadsheet shows the cost of the West Farnum to Sherman Road line as a line item for the relevant Interstate Reliability options.

For the new 345-kV route from National Grid's Millbury Switching Station in Millbury, MA through its Carpenter Hill Station in Charlton, MA, to CL&P's Manchester Substation in Manchester, CT, two potential routes were identified. The first of these routes, designated Option C-1, would follow the more direct route between these terminal points. This route would be about 58.5 miles long, and would require a new right-of-way for a distance of approximately 39.2 miles, generally parallel and adjacent to the Interstate 84 corridor. The second variant, designated Option C-2, would entail a longer (approximately 73.53 miles) route along existing rights-of-way, generally east from the Millbury Switching Station to WMECO's Ludlow Substation, and from there south to Manchester. The two variants are shown in the following figure:

Figure 2-7: Interstate Reliability Options C-1 and C-2 Routes

2.3.3.1 Evaluation of Option C-1

The portion of the C-1 route between Millbury and Carpenter Hill would follow existing rights-of-way and appears to be practical in all respects. However, of the approximately 42.5 miles between Carpenter Hill and Manchester, approximately 40 miles of the line would be on a new right-of-way developed adjacent to, or within, the I-84 highway corridor in Massachusetts and Connecticut. While collocation of an electric transmission line with an existing transportation corridor can reduce the width of the required new ROW, as compared to that required when there is no existing corridor, collocation with I-84 in this case would present engineering, cost, and permitting challenges that render this route undesirable.

Conceptual I-84 Route for Option C-1

CL&P's engineering consultants identified an alignment that would take these restrictions and challenges into account. The alignment would cross the highway approximately 12 times from one side to the other; and pass over portions of interchanges another 10 times. Such crossings increase the cost of the line because the line angles and long spans require very large angle structures, and work hours and work practices are limited by traffic considerations.

Most importantly, in order to avoid the taking of any homes or businesses, the line would need to longitudinally occupy the Connecticut Department of Transportation (ConnDOT) right-of-way lengthwise for approximately 3.8 miles, mostly in Vernon and Manchester.

If the line could be placed entirely within the highway right-of-way for that 3.8-mile distance, the remaining approximately 36 miles of the I-84 portion of the C-1 ROW would require 51 feet of easement on private property, thus requiring that a total of approximately 220 acres of private property be acquired.

The Option C-1 route along the Connecticut I-84 corridor would traverse linearly along the Hockanum River, as well as above water wells associated with Dobsonville Pond and Tankerhoosen Lake in Vernon. Other water resources along the route include the Walker Reservoir (East and West) in Vernon; Chopins Meadow Brook, Tolland Marsh Pond, the Skungamaug River, Grapevitis Brook, School Brook, and Labonte Brook in Tolland; the Willimantic River (which forms the border between Tolland and Willimantic); and the southern portion of Hamilton Reservoir near the Massachusetts border. The route also would cross portions of the Nye-Holman State Forest, Nipmuck State Forest, and Morey Pond Fish and Wildlife Management Area; it would abut the Bigelow Hollow State Park and Maschapaug Pond (in Union).

In Massachusetts, the Option C-1 alignment along I-84 would cross linearly along or near several watercourses and wooded riparian corridors, and also would cross an extensive wetland complex associated with Hobbs Brook, Cedar Pond, and Walker Pond. In Sturbridge, the route would traverse several developed areas near highway interchanges.

Along the entire I-84 segment, the development of the Option C-1 overhead 345-kV transmission line would be highly visible to travelers on I-84. In addition, Option C-1 would require the removal of a forested vegetation (both upland and wetland) adjacent to residential areas along the new transmission line corridor, opening these areas to views of the highway as well as the new transmission line. In many areas the entire forest buffer between the highway and adjacent residential areas would be removed. Further, the development of the new transmission line along the Option C-1 route would result in significant environmental effects associated with the creation of a new corridor, particularly in areas where extensive wooded wetlands and forest land would have to be removed.

Permitting Issues

In order to locate structures or conductors within the highway right-of-way, the TOs would be required to obtain the consent of the Connecticut and Massachusetts highway authorities. The "Policy on the Accommodation of Utilities on Highway Rights-of-Way." of the ConnDOT does not allow longitudinal installations of transmission lines unless it is not feasible to accommodate them elsewhere. The availability of existing transmission rights-of-way to accommodate this line (Options A and C-2) provide other ways to comply with this policy and would likely result in ConnDOT denying access to these rights-of-way. The policy of Massachusetts Highway Department (MassHighway) is to minimize the need for utilities to access and maintain facilities within interstate highway layouts.

Due to these ConnDOT and MassHighway policies, a completely new right-of-way adjacent to, but outside of the I-84 corridor would be necessary. Establishment of such a new corridor when existing corridors are available would be contrary to the policies of environmental permitting agencies such as the USACE and of the relevant siting authorities, which disfavor the development of new rights-of-way when existing rights-of-way between the same points are available.

Constructability Issues

Although the use of the I-84 corridor was determined to be unlikely, the TOs sought to identify a route along the highway corridor that would comply with the requirements of the highway authorities as nearly as possible, while still minimizing the amount of new right-of-way required. The baseline design to accomplish these objectives would be a vertical single-pole design that would reduce the right-of-way width required to 100 feet. Ideally, the structures would be located just outside of the edge of the highway right-of-way. In this scenario, 51 feet of new right-of-way over private land would be required and 49 feet of aerial easements for the conductors would be required from the highway authorities. Such easements would allow conductors (but not support structures) to be within the highway right-of-way, and would thus limit the height of objects such as signs, light standards, or bridge elements erected in the same location.

Such a route would encounter significant constructability challenges. Where a line is constructed adjacent to or across a limited-access highway right-of-way:

- Access needs to be established so that the line could be constructed and maintained from outside the DOT right-of-way
- Elevated portions of highways make placing poles difficult and costly.
- Rock outcroppings and cuts pose serious difficulties in locating the line and in constructing it
- Traffic considerations require work restrictions during construction, which adds to the cost of construction.

Where the facilities must be located longitudinally within an interstate highway right-of-way and if the highway authorities were to grant the necessary permissions, additional rigorous requirements would apply, including the following:

- Poles must be set back from the pavement to maintain a clear zone

- Poles must be set back beyond the toe of the side slopes
- Poles must not interfere with drainage of the highway
- Poles must be located to provide adequate clearance for traffic, highway signage and billboards, and sound walls
- Poles must not interfere with interchanges, including highway exit and entry ramps
- Poles must be located and appropriately sized to span over passes and under passes of roads and rail lines crossing the highway

Option C-1 Cost

The estimated cost of Option C-1, which assumes that the line could be located within the I-84 highway ROW as necessary to avoid takings of homes and commercial buildings, but includes an allowance for the difficulties and restrictions on construction along the highway, is approximately $532 million, making Option C-1 the second most expensive AC Option, even though it would be the shortest in length.

Option C-1 Conclusion

Since a route along existing electric transmission rights-of-way between the same terminal points is available, the TOs evaluated as very low the likelihood of obtaining permits from the highway authorities that would be necessary to locate the line along and within the highway corridor. Moreover, even if the necessary permits for the I-84 portion of the route could be obtained, the difficulties and high cost of construction, as well as substantial environmental impacts, along this portion of the route would nevertheless make it less desirable than other available alternatives. Accordingly, the C-1 route was determined to be impractical, and, and further analysis of Option C was limited to Option C-2. That further analysis will be reviewed after the following explanation of the evolution of Option D, and its relation to Option C-2.

2.3.4 Evaluation of Interstate Reliability Option D

Interstate Reliability Option D was described in the *Options Analysis* as follows:

> Interstate Option D builds a new 345 kV line from Millbury to Carpenter Hill to Ludlow and takes advantage of the proposed Springfield area improvements to complete the interstate connection. It also requires uprating of the 345 kV lines from Ludlow to Manchester and from Sherman Road to the state border. A new line from Sherman Road to West Farnum also is required.
>
> *Options Analysis*, p. 18

The following one-line diagram of the major improvements contemplated by Interstate Reliability Option D was provided at p. 19 of the final *Options Analysis.*

Figure 2-8: Interstate Reliability Option D[20]

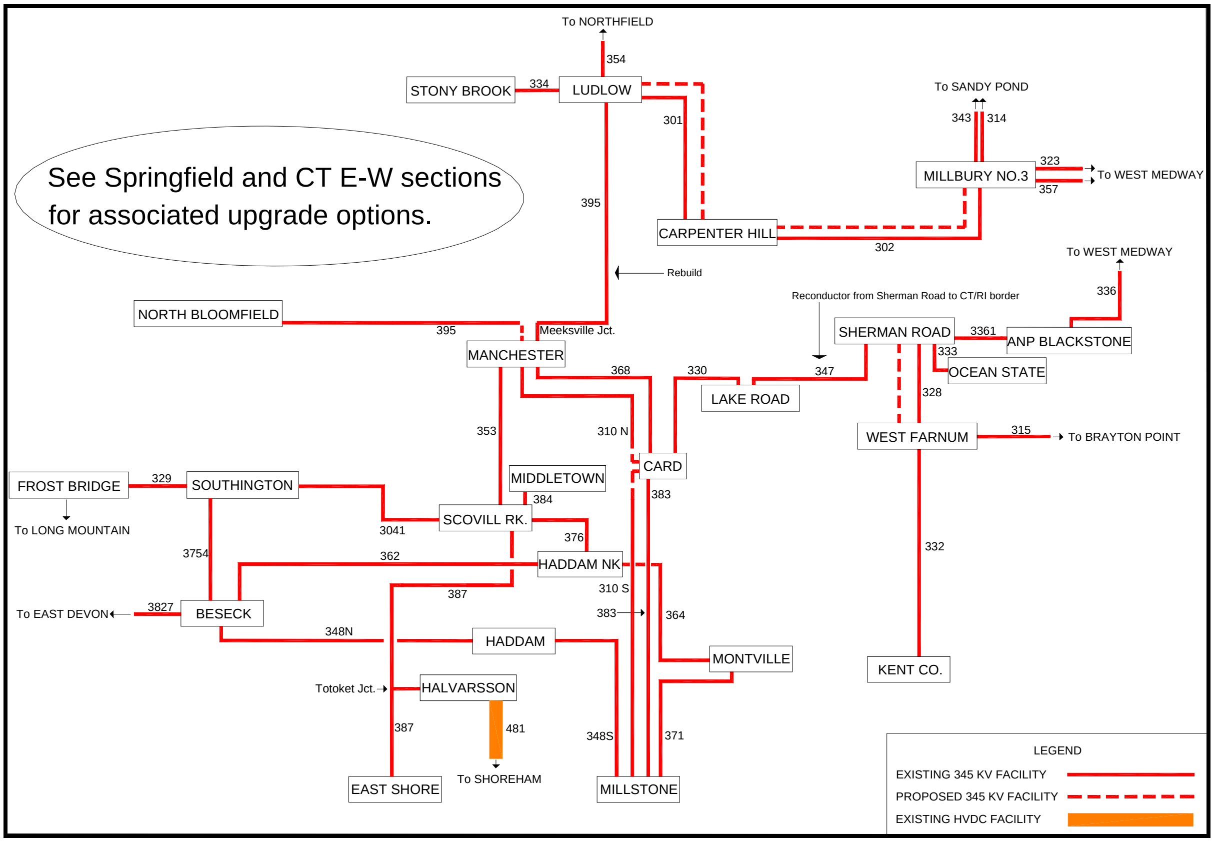


Table A-1 in the *Options Analysis*, at page 55, makes clear that the authors assumed that the “uprating” of the existing 345-kV line between Ludlow and Manchester could be accomplished by reconductoring the existing line with bundled 1272-kcmil ACSR conductors.

2.3.4.1 Further Evaluation of Interstate Reliability Option D

The configuration of Interstate Reliability Option D was thus quite similar to that of Interstate Reliability Option C-2, with the notable exceptions that Option D contemplated increasing the capacity of the Ludlow to Manchester path by reconductoring the existing 345-kV line on that right-of-way (a distance of approximately 31.6 miles), rather than by building a new line; and also reconductoring of the 345-kV line from Sherman Road to the Connecticut/Rhode Island state border. The two options are shown together below.

[20] Source: *Options Analysis* Figure 4-4.

Figure 2-9:
Interstate Reliability Option D – Route

Figure 2-10:
Interstate Reliability Option C-2 – Route

Changing out the conductors on an existing set of support structures (as Option D contemplated) is, of course, much less costly than building an entirely new line (conductors and support structures.) Accordingly, as conceived, Option D had the potential of being one of the more economic alternatives. However, a structural engineering study of the capability of the existing 345-kV line structures on the Ludlow to Manchester right-of-way determined that fewer than 20% of the structures on the Massachusetts segment, and fewer than 5% of the structures on the Connecticut segment, could support bundled 1272–kcmil ACSR conductors. Accordingly, there was no opportunity to reduce costs by reconductoring the existing 345-kV line on the Ludlow to Manchester right-of-way. To support conductors of the required capacity, a new set of 345-kV line structures would have to be built alongside the existing line structures. If the objective were to achieve the exact configuration assumed by the Option D modeling, the existing structures and conductors could be removed from the right-of-way after the new 345-kV line was built, at yet more expense. However, since the existing 345-kV line has continued usefulness, that possibility was not seriously considered. When Option D is modified to include a new 345-kV line, rather than reconductoring of the existing 345-kV line, it becomes very similar to Option C-2, with the only difference being that Option D also includes a reconductoring of the existing 345-kV line between the Sherman Road Substation and the Rhode Island/Connecticut border, and Option C-2 does not. The reason for this difference is that the modeling summarized in the *Options Analysis* determined that, if the 345-kV line from Ludlow to Manchester was reconductored with 1272-kcmil ACSR conductors, the Sherman Road to the border segment would become the limiting element for N-1 CT import capacity. In the design of Option D, this limitation was mitigated, and the design criteria of an improvement to the CT N-1 import capacity greater than 923 MW was satisfied by reconductoring the Sherman Road – CT border segment. However, if a new 345-kV line were built between Ludlow and Manchester, as in Option C-2, the design criteria would be easily satisfied without any reconductoring of the Sherman Road – state border segment.

2.3.4.2 Option D Conclusion

In summary, Interstate Reliability Option D turned out to be not constructible as assumed in the *Options Analysis;* and when necessary modifications are made to the hypothesized configuration, it becomes indistinguishable from Interstate Reliability Option C-2. Accordingly, Option D was not further analyzed as a distinct transmission alternative.

2.3.5 Comparative Evaluation of Interstate Reliability Option A and Interstate Reliability Option C-2

The elimination of Options B, C-1, and D left as the "finalists" Option C-2 and Option A. These options were compared on the basis of their respective system benefits, cost, and routing characteristics (both environmental and social impact.) While both options had considerable merit, the ultimate choice of Option A was a clear one.

2.3.5.1 Comparison of System Benefits of Interstate Reliability Options A and C-2

As presented in the *Options Analysis* tables, the "system performance factors" of Interstate Reliability Options A and C-2 were quite similar, although Option A was either equal to or better than Option C-2 in all categories. These factors were presented in Tables 4-2 (Option A) and 4-4 (Option C). The following table presents these results in a comparative format:

Table 2-6: System Benefits Comparison[21]

System Performance Factors	A		C-2	
Effect on transfer capability between New York and New England	Positive effect; Equivalent per §4.3.9	X	Positive effect; equivalent per §4.3.9	X
Improving New England east-west transfer capability	+1376 MW to 4174 MW	X	+1293 MW to 4091 MW	
Improving Connecticut's Import capability:				
N-1	+1766 MW to 4443 MW	X	+1766 MW to 4443 MW	X
N-1-1	+1591 MW to 2783 MW	X	+1535 MW to 2727 MW	
Eliminating high line loadings under contingencies (2016)	3 all-lines-in 43 line-out 46 Total	X	6 all-lines-in 67 line-out 73 Total	
Improving system voltages during contingencies (2016) (# borderline voltage cases following N-1 contingencies)	6	X	8	
Decreasing system losses (reduction as compared with pre-project system)	56 MW		69 MW	X
Decreasing short-circuit duty (increase on worst location)	8.9%	X	9.3%	

In addition, Option A made a greater contribution to system stability than Option C-2 (*See, p 16, supra);* was preferred by the operations personnel; and can be tied into Lake Road, potentially thereby making the Lake Road units eligible to be counted toward Connecticut's local sourcing requirement.

Accordingly, the TOs determined that, with respect to the system benefits they offered, Option A was superior to Option C.

2.3.5.2 Comparative Costs of Interstate Reliability Options A and C-2

The relative costs of Interstate Reliability Options A and C-2 are set forth in the Interstate Reliability Options Cost Spreadsheet, Appendix Item 1. The estimated "fully loaded" cost for Option A is approximately $460 million whereas the cost for Option C-2, estimated on the same basis, is $496 million.

[21] Source: *Options Analysis* Tables 4-2 and 4-4.

However, the spreadsheet comparison does not take into account another cost item that would be caused by the choice of Option C-2 over Option A – the incremental cost caused by the separation of 345-kV and 115-kV circuits currently on double-circuit structures between Manchester Substation and Meekville Junction. As explained in the "Solution Report for the Springfield Area" dated April 23, 2008 (at pp. 2-43 – 2-44), the separation of these circuit segments will be required as part of the Greater Springfield Reliability Project. The separation, as currently planned, can be simply accomplished by erecting a new vertical line segment. The fully-loaded cost of this work is estimated at $18 million.

If the Manchester – Meekville circuit separation were accomplished as planned, there would be no room left on the right-of-way for the new 345-kV line that would be required by the C-2 Option. In order to provide such room, a more complex and expensive construction effort would be required for the line separation, at an incremental cost of approximately $27 million.

2.3.5.3 Comparison of the Routing and Environmental Impacts of Interstate Reliability Options A and C-2

Although Option A performed better and cost less than Option C-2, they were sufficiently comparable to require a detailed comparison of the social and environmental impacts before a final selection was made. Such a comparison was performed by ENSR, Burns & McDonnell, and Phenix Environmental, and is provided in Appendix Item 3: Comparative Routing Analysis of Option A and Option C-2. Option A was found to be preferable from a routing and environmental perspective.

As compared to Option A, Option C-2 would involve:

- More construction: Option C-2 would require 83.4 miles of new 345-kV line, or 7 miles more (9%) than Option A.
- Greater impacts to wetlands, as designated on National Wetland Inventory maps. Option C-2 would traverse approximately 385 acres of wetlands, compared to approximately 242 acres along Option A.
- Alignments through or near more areas of known habitat for state or federally-listed protected species (i.e., threatened, endangered, or special concern species). Option C-2 would traverse or be located within 500 feet of approximately 484 acres of such mapped habitat, compared to 149 acres along Option A.
- Alignment through more park or other designated public lands, such as wildlife management areas. Option C-2 would cross approximately 330 acres of such public lands, including Wells State Park in Sturbridge. In comparison, Option A would traverse approximately 244 acres of

public lands, including Mansfield Hollow State Park and Mansfield Hollow Wildlife Management Area.

- Alignments in proximity to 47% more residences than along Option A. Portions of Option C-2 would traverse through more densely populated areas, resulting in an estimated 684 homes within 500 feet of the route centerline. In comparison, Option A would be aligned within 500 feet of 466 homes.

Both options would be developed within existing transmission line easements, but Option A would potentially require additional easement (i.e., ROW expansion) through portions of Mansfield Hollow State Park and the Mansfield Wildlife Management Area in the Connecticut towns of Mansfield and Chaplin. As proposed, Option C-2 would not involve any additional ROW acquisition. However, if the Greater Springfield Reliability Project is developed as proposed between Manchester Substation and Meekville Junction, or if the GSRP "noticed alternative Southern Route" is selected for the project between Hampden Junction and Ludlow Substation, substantial additional ROW would have to be acquired to accommodate the Interstate 345-kV line along these segments of Option C-2. Further, the supplemental expansions of these ROW segments would result in potentially significant additional environmental effects if the existing utility corridors must be widened into previously undeveloped upland and wetland forested areas.

3.0 CONCLUSION

The *Options Analysis* conducted by the ISO-NE working group determined that five electrical "Options" met minimal performance objectives. The TOs analyzed these five options and a routing variation on one of them for a total of six options. Of these six analyzed options, two AC options – Option A and Option C-2 were clearly superior to the others. As between these two, Option A offers greater system benefit, lower cost, and lesser environmental impact. Accordingly, the TOs have selected Option A as their preferred solution.

APPENDIX ITEM 1

Interstate Reinforcement Options

Descrpiton	A	B	C-1	C-2	D	E	Length (miles) or Each
	Interstate Option Designations						
	Millbury - Card	Montville-Kent Cty	Millbury - Manch (I84)	Millbury - Manch (via Ludlow ROW)	Millbury - Ludlow	HVDC	
Build 345-kV circuit from Card to Lake Road	X						29.3
Build 345-kV circuit from Lake Road to Rhode Island Border	X						7.5
Build 345-kV circuit from Rhode Island Border to W. Farnum + W. Farnum Sub Upgrades	X						17.7
Build 345-kV circuit from W. Farnum to Millbury + Millbury #3 Sub Upgrades	X						20.7
Build 345-kV circuit from Montville to Rhode Island Border		X					18.3
Build 345-kV circuit from Rhode Island Border to Kent County + Kent County Sub Upgrades		X					32.7
Build 345-kV circuit from Manchester to Carpenter Hill (I-84 Corridor)			X				42.4
Build 345-kV circuit from Ludlow to Manchester				X			31.6
Build 345-kV circuit from Manchester to Meekville Junction; Split #395 to attach new line					X		2.5
Build 345-kV circuit from Carpenter Hill to Millbury + Millbury #3 Sub Upgrades			X	X	X		16.03
Build 345-kV circuit from Ludlow to Carpenter Hill + Carpenter Hill Sub Upgrades				X	X		25.9
Reconductor 345-kV circuit from Carpenter Hill to Millbury 302 ln + Millbury #3 Sub Upgrades		X					16.03
Reconductor 345-kV circuit from Ludlow to Carpenter Hill 301 ln (23.1 mi. NG, 2.8 mi. NU - NG $/mi. used)		X					25.9
Reconductor 345-kV circuit from Sherman Rd. to ANP Blackstone 3361 ln + S.R. Sub Upgrades		X					8.67
Build 345-kV circuit from Sherman Rd. to W. Farnum 2nd line + W.F and S.R. Sub Upgrades			X	X	X	X	9.03
Reconductor Sherman Rd - RI/CT 347 ln	X				X		8.67
Upgrade Terminal Equip Sherman Rd, Blackstone 3361 ln	X			X	X		1
Upgrade Terminal Equip Sherman Rd, W Farnum 328 ln		X					1
Upgrade S171S Drops at Hartford Ave Sub		X					
Upgrade T172S Drops at Hartford Ave Sub		X	X	X		X	
Reconductor Hartford Ave.-Johnston Tap S-171S + Hartford Ave Sub Upgrades	X		X	X	X	X	1
Reconductor Hartford Ave.-Johnston Tap T-172S + Hartford Ave Sub Upgrades	X				X		1
Upgrade 115 kV Terminal Equipment at Brayton Point and Wampanoag Subs		X					
Upgrade 115 kV Franklin Sq Sub Breakers		X					
Install two 63 MVAR Capacitors at Kent County Sub	X		X	X	X	X	
Reconductor Somerset-Swansea 115 kV W4 + Sub Upgrades		X	X	X	X	X	4.5
Reconductor Medway-Depot st. D-130		X		X	X	X	5
Reconductor MPLP-Depot St. C-129		X			X		0.5
Reconductor W. Charlton - Little Rest W-175		X				X	9.3
Reconductor Little Rest - Palmer W-175		X	X	X			6.6
Rebuild #395 line from Ludlow CT/MA Border					X		11.73
Rebuild #395 line from CT/MA Border to Manchester					X		19.9
Build a HVDC bi-pole from Millbury to Southington						X	1
Build a Connecticut East-West solution, see alternate table	X	X	X	X	X		0
Loop the #310 line from Millstone to Manchester into Card	X	X	X	X	X		3.8
Terminal equipment at Millstone & Manchester	X	X	X	X	X		
Reconfigure Card substation to breaker-and-a-half and add terminals (310 Loop)	X	X	X	X	X		
Substation Work Not in the Original Options							
Killingly S/S - Add 345-kV deadend and circuit breaker	X						
Lake Road - Add 4th bay. terminal and circuit breakers	X						
Card S/S - add line terminals for line to Lake Rd	X						
Manchester S/S			X	X	X		
Montville S/S		X					
General Protection Issues	X	X	X	X	X	X	
Project Totals (in $Millions, 2008 estimate year)	**$ 377**	**$ 506**	**$ 435**	**$ 402**	**$ 430**	**> $1,500**	
Project Totals (in $Millions, fully escalated)	**$ 460**	**$ 629**	**$ 532**	**$ 496**	**$ 531**	**$ 2,291**	
Northeast Utilities Project Totals (in $Millions, Fully Escalated)	**$ 251**	**$ 323**	**$ 392**	**$ 254**	**$ 272**		
National Grid Project Totals (in $Millions, Fully Escalated)	**$ 209**	**$ 306**	**$ 140**	**$ 242**	**$ 259**		

APPENDIX ITEM 2

GE Energy

Final Report

Applicability of an HVDC Option in the NEEWS Upgrades

Prepared for:

Northeast Utilities and National Grid

August 8, 2008

FOREWORD

This document was prepared by General Electric International, Inc. It is submitted to Northeast Utilities and National Grid. Technical and commercial questions and any correspondence concerning this document should be referred to:

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TABLE OF CONTENTS

1. INTRODUCTION

Northeast Utilities and National Grid are planning transmission system reinforcement projects intended to resolve reliability problems in the southern portion of the ISO-New England system. There are several alternative designs for components of these projects, known as the New England East-West Solution (NEEWS). Most of the alternatives for NEEWS use 345 kV ac transmission lines and cables. One alternative, however, proposes an HVDC line between the Millbury switching station in East-Central Massachusetts and the Southington substation in Central Connecticut. Separate planning studies, not in the scope of this report, have determined that the appropriate continuous capacity rating for this HVDC alternative is 1000 MW.

HVDC transmission has unique design, system integration, expandability, and operability characteristics which distinguish this technology from an ac transmission alternative. The purpose of this report is to assess the applicability of HVDC transmission to the NEEWS design, with specific consideration of the proposed Millbury-Southington line, as defined by other planning studies. This report begins by summarizing the key characteristics of HVDC transmission technology, describing how this technology fits within an ac system, and summarizes the application factors that have historically been the decisive motivators of HVDC projects in North America and around the world. With this background, the application requirements for the NEEWS project are compared with these proven justifications for HVDC applications.

2. OVERVIEW OF HVDC TRANSMISSION

The vast majority of electrical energy used in the world moves from the generators to the end-use customers exclusively over alternating current (ac) transmission lines and cables. Although Thomas A. Edison began the electrical industry using direct current (dc) distribution of power from local generating plants to nearby loads, ac very rapidly replaced dc in the late 1800's when the inherent efficiency of ac technology was realized. Unlike dc, ac can be easily stepped up or down in voltage by transformers, allowing power to be generated, stepped up to a high voltage for transmission over considerable distances, and then stepped down to a low voltage for consumer use. Because power is proportional to the product of current and voltage, high-voltage ac transmission allows large amounts of power to be moved over reasonably sized conductors, and losses and voltage drop are acceptably small.

Advances in power electronic technology in the 1930's to 1950's facilitated development of equipment that can convert ac to dc and dc to ac at high voltage levels. By so doing, power can be generated as ac in one location, stepped up to a high voltage, converted to dc, transmitted, and then converted back to high-voltage ac, and stepped down for utilization. As will be discussed later, the transmission of power as high voltage dc (HVDC) can be more efficient than ac when distances are long, and allows decoupling of the frequencies of the sending and receiving ac systems.

Since its commercial application over half a century ago, the world-wide base of installed HVDC transmission capacity has grown steadily. Although the total world-wide HVDC capacity exceeds 60,000 MW, this is a miniscule fraction of the total worldwide production of electric power. HVDC has been, and remains, a niche solution for specific categories of applications where it can provide a superior alternative to ac for performance or economic reasons.

2.1. DC vs. AC Power Flow

The fundamental physics of HVDC and ac power transmission result in distinct natural laws governing power flow. In HVDC transmission, the flow of power is proportional to the difference in voltage between the sending and receiving end, divided by resistance. This is analogous to water flow in a pipe being proportional to the differences in pressures, divided by the flow resistance of the pipe. Figure 1 describes the power flow law for direct current (*P* represents power, *U* represents voltage, and *R* resistance). Because the power conversion process, indicated by the symbols at the left and right side of the drawing, allows precise control of the direct voltage, the power flow over an HVDC line can be tightly controlled. The flow is also essentially independent of small changes in the ac systems connected to each converter.

$$P_1 = \left(\frac{U_1 - U_2}{R_{12}}\right) \cdot U_1$$

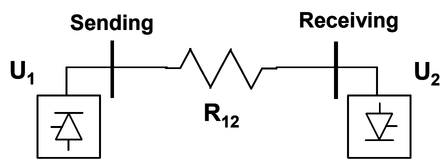

Figure 1- Power flow on an HVDC line.

Power flow over an ac line is primarily determined by the phase angle of the ac voltages, divided by the inductive reactance of the line. The inductive reactance of an overhead line can be an order of magnitude greater than its resistance, which is ignored in this simplified flow law. The ac line flow law is illustrated in Figure 2, where δ indicates phase angle, and X indicates the inductive reactance of the line. The phase angle of the bus voltage cannot be directly controlled, except by expensive phase-shifting transformers or by recently-introduced FACTS (Flexible AC Transmission Systems) power electronic equipment. Voltage phase angles are the natural result of the injections of power by generators, extractions of power by loads, and the impedances (reactances and resistances) of the network. Thus, ac power tends to flow in patterns defined by the fixed system characteristics, and are not usually directly controlled.

$$P = \frac{U_1 \cdot U_2}{X_{12}} \cdot \sin(\delta_1 - \delta_2)$$

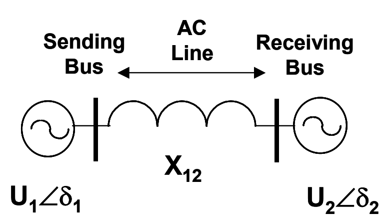

Figure 2 – Power flow on an ac line.

The sine of the difference in phase angles reaches a maximum value of one when the angles are ninety electrical degrees apart. Thus, there is a maximum theoretical power flow over an ac line, in addition to any constraints on current due to conductor heating. Because transmission line reactance increases proportionally to distance, line reactance presents a significant constraint to exploiting the current-carrying capability of a very long (many hundreds of miles) ac transmission line. Very long ac transmission lines often use series capacitors to cancel some of the line reactance and increase the line's loadability.

System disturbances tend to make phase angles change dynamically. An increasing phase angle difference results in an increased power flow, which tends to arrest the increase of phase angle separation. However, if the ninety-degree point is reached, further increases of angle decrease power flow and the phase angles can continue to separate. This is an unstable condition, known as transient instability. Transmission planners have to design in adequate transmission capacity to avoid this instability which can result in system breakup and blackouts.

HVDC system can decouple the angular disturbances in one system from another. On the other hand, an HVDC system has no natural tendency to increase power flow to arrest angular separation. The first attribute is useful when building a transmission line <u>between</u> relatively independent systems, the latter attribute has adverse impact if an HVDC line is used <u>within</u> an otherwise tightly coupled ac system.

2.2. Types of HVDC Technology

There are two fundamentally different approaches to the conversion of power between ac and dc systems. Until the past decade, all HVDC transmission systems used "system commutated converters", which we refer to as "conventional HVDC" in this report. More recently, a very different technology, called voltage source converter HVDC (VSC-HVDC) has become available. The similarity in these two technologies is that they both take power from ac systems, convert the power to dc, and convert back to ac at a different location. Other characteristics of these technologies are generally quite dissimilar.

In conventional HVDC, the ac phases are sequentially connected to the dc line using thyristors, and this interconnection is shifted twelve times per cycle of the ac voltage. The shifting of current from one connection to another, called commutation, requires that the ac system have sufficient strength. This switching process also creates a large amount of harmonic currents, and creates a large demand for reactive power at each converter terminal. Large amounts of harmonic filtering are necessary to maintain power quality and avoid interference with telephone lines. These filters, by inherent nature of their design, also generate reactive power that partially fulfills the converter's demand. Additional capacitor banks are required to provide all the reactive power required when operating at rated power transmission capacity.

Voltage source converters technology synthesize an ac voltage by rapidly turning on and off large transistors a thousand times or more per second. Although this rapid switching generates a large amount of harmonics, these harmonics can be mitigated by relatively small filters because the harmonics are generated at high frequencies. A VSC-HVDC converter can be controlled to produce or absorb reactive power, independent of the dc power flow. This allows regulation of the ac bus voltage, as desired. This also means that large capacitor and filter banks are not required, unlike conventional HVDC systems.

Because VSC-HVDC technology is so new, there is only one European manufacturer having commercial experience. Another European manufacturer is presently involved in the design and construction of their first VSC-HVDC project.

2.3. HVDC System Configurations and Terminology

2.3.1. Conventional HVDC Configurations

HVDC transmission systems using overhead dc lines are nearly always configured in a bipolar configuration. A simple **bipolar** HVDC system is illustrated in Figure 3. The station where ac is converted from ac to dc, and vice versa, is called a **converter station** or **converter terminal**. A bipolar HVDC line has two conductor groups insulated for high voltage. (The term conductor group is used here because there may be a single conductor or a bundle of paralleled conductors.) One conductor group is at a positive potential relative to ground and the other conductor group is at a negative potential. At each terminal, there is a converter connected to each conductor group. The terminal where ac power is converted to dc is called the **rectifier**, and the terminal where power is converted back to ac is called the **inverter**. The equipment of a rectifier and inverter are identical, and most HVDC systems are designed for bi-directional flow of power.

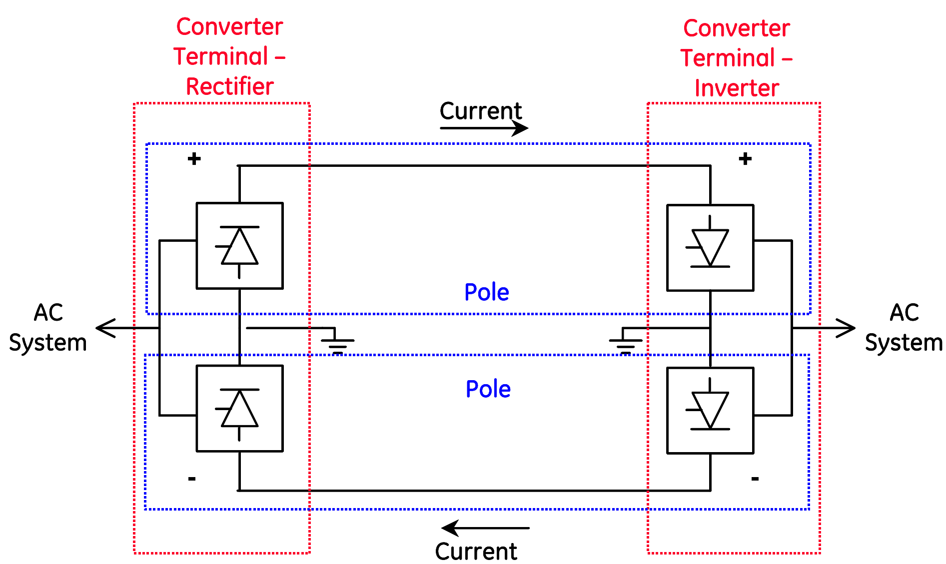

Figure 3 – Bipolar HVDC system.

The converters connected to one polarity at the rectifier and inverter, and the conductor group on the line, are called a pole. A bipolar system has two **poles**, and current flows as shown, no matter which way power flows. Power reversal is accomplished by reversal of voltage polarity (positive pole becomes negative, and vice versa) simply by control action. Most HVDC lines have high-current **electrodes** connecting the midpoints between poles to earth. The currents of the two poles are usually maintained at identical magnitudes, thus there is normally no dc flow through the earth. If one pole should become inoperative, at least 50% of power transmission capacity can be maintained by using **monopolar earth return** operation, shown in Figure 4. If the outage of a pole is caused by unavailability of the converter on one pole, then the conductors of that pole can be reconfigured to operate as the return conductor, as shown in Figure 5, for **monopolar metallic return** operation of the functioning pole.

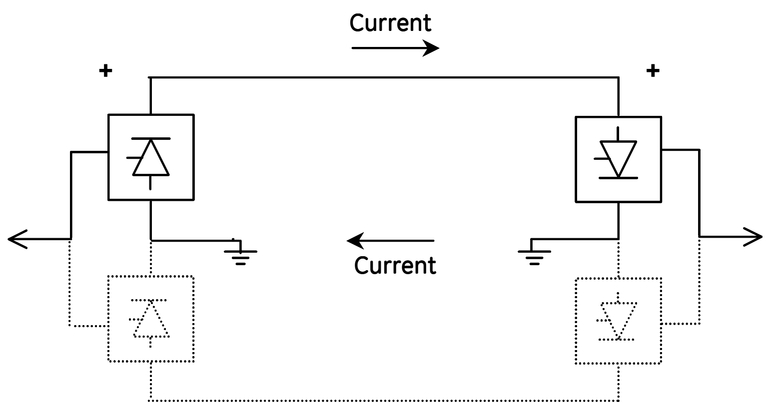

Figure 4 – Monopolar earth return HVDC operation.

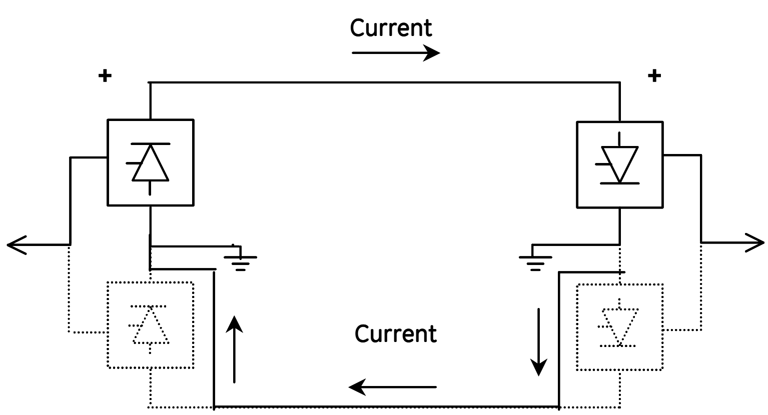

Figure 5 - Monopolar metallic return HVDC operation.

Some HVDC systems are designed as monopoles, such as illustrated in Figure 6. There is usually a low-voltage return conductor to complete the circuit, although there are some monopolar HVDC systems using earth or sea electrodes on a continuous basis. This is no longer acceptable under the National Electrical Safety Code in the U.S. The monopolar configuration provides less redundancy than a bipole, and is most often used in shorter-distance undersea or underground HVDC cable systems. Cable systems are less susceptible to line outages, and thus the redundancy of a bipolar system is less important. Because of the benefits of scale, the same converter capacity in one monopole is less expensive than the same capacity divided between two converters in a bipole. Line costs per MW-mile are less for a bipole than for a monopole with a return conductor. Thus, the general tendency for this configuration to be used for shorter distance transmission.

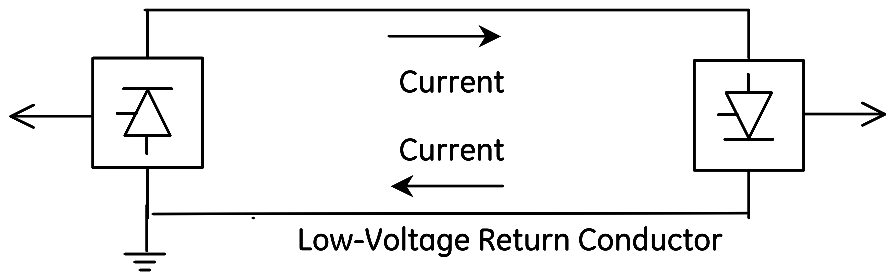

Figure 6 – Monopolar HVDC system.

Almost all HVDC transmission line systems have only two terminals. Technology has been developed to allow an HVDC system to have more than two terminals; a multi-terminal system. Although this technology has existed for over two decades, it is employed with extreme rarity. It should be noted that the New England – Hydro-Quebec transmission line was originally designed for five terminals; Radisson, Nicolet, and Sandy Pond rated 2000 MW and Comerford and Des Cantons rated 690 MW. It was realized that the low-rated terminals, particularly the Comerford terminal that is connected to a weak ac system, compromised the performance of the multi-terminal system. Comerford and Des Cantons have since been removed from active service. The remaining HVDC system is almost always operated two terminals at a time.

HVDC circuit breakers, capable of interrupting fault current, are not commercially available. No multi-terminal HVDC system uses an HVDC circuit breaker to interrupt a faulted line section. Instead, the entire pole must be shut down, the faulted section isolated when deenergized, and the remaining system restarted. This is in contrast to ac transmission systems for which circuit breakers are available to isolate a faulted line section without any system shutdown. In summary, although multi-terminal HVDC exists and has been reduced to practice, there are significant issues that make this configuration less desirable.

Sometimes HVDC transmission is used to interconnect adjacent ac system which are not synchronized. In this case, the rectifier and inverter are located in one terminal, typically in the same building. This is called a back-to-back HVDC system.

2.3.2. VSC-HVDC Configurations

All VSC-HVDC systems constructed to date use a modified bipolar configuration and underground or undersea cables. There are two cables, energized to opposite potentials by a single converter at each terminal. These systems are not operable in a monopolar configuration.

As illustrated in Figure 7, power reversal in a VSC-HVDC system is accomplished by reversal of current direction, in contrast with a conventional HVDC system where power reversal is accomplished be reversal of polarity.

There are presently new VSC-HVDC systems under contract having a bipolar configuration and overhead transmission line, similar to that shown in Figure 3 for conventional HVDC, and another with a monopolar metallic return undersea cable configuration similar to Figure 6.

In theory, VSC-HVDC can be applied in a multi-terminal configuration. No such systems have been constructed, however.

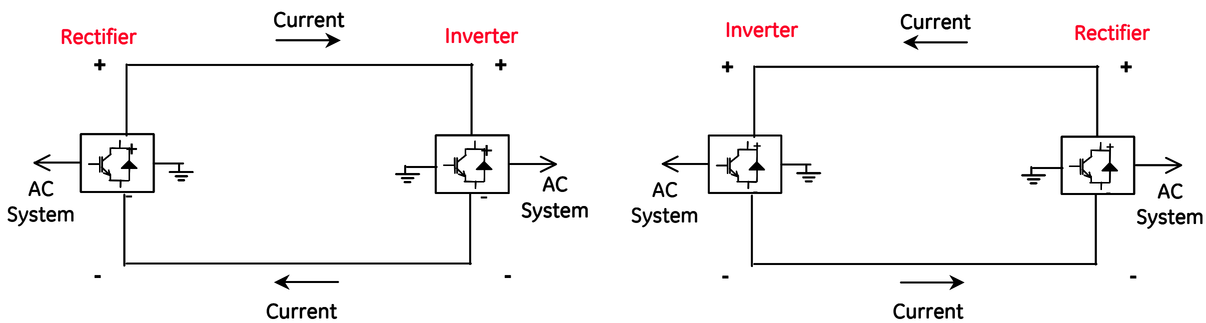

Figure 7 – VSC-HVDC system with bipolar line and single converter per terminal, showing both power flow directions.

3. AC AND HVDC TRANSMISSION ECONOMIC FACTORS

It cannot be stated that either ac or HVDC transmission technology is more or less expensive than the other, on a global basis. In some instances HVDC can have a smaller first costs and a smaller operating cost than an ac line or group of lines having the same capacity. In other instances, HVDC is more expensive but might be the only viable solution for technical reasons.

3.1. Terminating Stations

At the terminals of an ac line, all that is required is a substation with circuit breakers and protective relays. HVDC converter stations are complex and costly installations. In addition to the ac circuit breakers needed to tie into the ac system, there are many major components of a conventional HVDC converter terminal including:

- Converter valve assemblies, composed of the power-electronic thyristors and auxiliary equipment to perform the conversion process, including a cooling system for the power electronics. Modern HVDC systems employ water cooling, using highly purified water such that it remains electrically non-conductive when piped to the power electronics which are elevated hundreds of kV above ground potential.
- Converter transformers. These large, specially designed transformers step the ac voltage to the value needed to interface with the HVDC system, and provide isolation from the high dc voltage.

- Smoothing reactors, to limit the rate of change of direct current, and to smooth the direct current in order to minimize interference coupled onto telephone lines running in the vicinity of an overhead HVDC line.
- AC harmonic filters divert harmonic currents produced by the converter to avoid negative impacts on power quality, and to avoid interference with telephone lines running near to ac lines connected to the HVDC terminal. The harmonic filters also provide reactive power to supply the large reactive power demand of the conversion process. Harmonic filters require a substation portion of the space in a converter station.
- Capacitor banks provide additional reactive power to compensate for the reactive demands of the conversion process, and to support the increased ac system reactive demand caused by power flow in or out of the terminal over the ac system. The total reactive power requirement of a conventional HVDC system, to serve both converter and typical ac system compensation needs, range from about 40% to 60% of the rated real power capacity. Typically, 60% to 75% of this reactive requirement is provided by the ac harmonic filters, and shunt capacitor banks provide the remainder.
- Shunt reactors compensate for reactive power generated by the ac harmonic filters that exceeds the reactive requirements of the conversion process and the ac system. Typically, these reactors are used at lower HVDC power levels where the harmonic filtering requirements exceed the converter reactive demand.
- DC harmonic filters work in conjunction with the smoothing reactors to divert harmonics on an overhead HVDC line. DC filters are not usually applied when the HVDC line is exclusively an underground or underwater cable because there is no coupling to telephone lines.
- Controls and protection. Redundant computers control all aspects of the terminal operation, from precisely firing the converter valves 720 times per second, to management of auxiliary cooling systems. Protective relays protect the large number of major components and subsystems from failure and excess duty. The converter valves and control/protection systems are typically housed in a large multi-story building.

Conventional HVDC converter stations occupy a space of many acres. A recent 660 MW HVDC project required twelve acres for a monopolar converter terminal. This was a compacted design due to the high real estate costs and limited availability of suitable land for the station.

Typical costs for an HVDC converter terminal are in the range of $100,000 to $200,000 per MW of rated capacity. Per-MW costs are less for a large installation, relative to a low-rated system. Also, per-MW costs increase with increasing dc line voltage. Increased line voltage, however, makes the line cost less per MW-mile. HVDC line voltage selection is a tradeoff between line and converter terminal costs, with lower HVDC voltages favored for shorter lines, and higher voltages for longer lines.

A VSC-HVDC terminal has less equipment, and occupies less space. The transformers used are ordinary units, not the special transformers required for conventional HVDC. Harmonic filters are much smaller, typically 10% to 20% of the power rating. Because the VSC-HVDC converters generate or absorb reactive power as desired, shunt capacitors and reactors are not needed.

The market for VSC-HVDC has not matured, with relatively few projects and only one experienced manufacturer and one new entrant. Thus, converter station costs are not as well defined as for conventional HVDC. This technology is economically advantageous for smaller applications, and conventional HVDC is advantageous for very large projects. The dominant manufacturer claims that the prices for the two technologies are equivalent in the range of 1000 MW system capacity[1].

3.2. Overhead Line Design Differences

The physical designs of overhead ac and HVDC lines differ substantially. AC lines have three conductors (or conductor bundles) and HVDC lines have two, but the differences go far beyond this obvious point. The clearances between an EHV ac line (345 kV and up) and the supporting tower, and ground, are governed by overvoltages produced by line switching. Providing this clearance adds to the size and strength requirements of the supporting structures. HVDC lines are not switched abruptly with circuit breakers, and so they do not experience as high of a switching transient. The controlling factor for HVDC line design is providing a sufficiently long insulator string such that the insulator can withstand the applied voltage when it becomes contaminated from dust, chemicals (e.g., salt, fertilizers), and moisture which tend to accumulate on the insulators due to electrostatic attraction.

An ac line does not utilize its full insulating strength all of the time because the voltage magnitude is continually oscillating in sine-wave pattern. The HVDC line is at or very near its full potential all the time when operating.

The continually-changing magnetic fields caused by current flow in an ac line interfere with the current flow such as to make most of the current flow near the outside perimeter of the conductor. Thus, the conductor is not fully utilized because of this “skin effect”. In an HVDC line, current density is uniform in a uniform conductor. This difference can be expressed as a difference in effective resistance between an ac and HVDC line, with the 60 Hz ac resistance up to 18% greater. In addition to consuming energy, the extra resistance heats the conductor, and conductor temperature is one limit to power flow over a line.

As a result of the factors just discussed, an HVDC line costs, per mile, approximately 30% to 40% less than an ac line of comparable capacity. This is a typical difference, and may vary by

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[1] Bahrman, M., “HVDC Applications”, Presentation at the New England ISO PAC Meeting, Westborough, MA, December 18, 2007.

application. For example, if right-of-way acquisition is a particularly large portion of line cost, then the differential may be less.

3.3. Underground and Undersea Cables

Underground and undersea cables have a large capacitance between the energized phase conductor and the grounded concentric cable shield. When energized with ac, this capacitance generates a large amount of reactive power. Stated differently, the capacitance passes a large current that leads the phase angle of the applied voltage by ninety degrees. Without regularly-spaced compensation along an EHV ac cable, the capacitive current can become larger than the load current. There is a distance, on the order of sixty miles in length, where a 345 kV ac cable can become thermally overloaded by excess capacitive current simply by being energized at one end, without any load current or path for load current. At shorter distances, the current capacity available to transmit power is diminished by the flow of the capacitive current. Figure 8 illustrates the impact of uncompensated distance on the available load-transmitting capacity of a typical 345-kV cross-linked polyethylene-insulated ac cable. If the cable is broken into shorter intervals, and shunt reactors are connected to compensate the capacitive current, this limitation can be mitigated. While compensation may be practical for underground cables, it is not practical to locate shunt reactors under water to compensate an under-sea ac cable. Even with compensation of the fundamental-frequency shunt capacitive reactance of an ac cable, the capacitance still affects system resonances. In the case of the recent Middletown-Norwalk transmission project in Connecticut, this capacitive impact on system resonant behavior was shown to render inadvisable the application of large amounts of ac cable in that system.

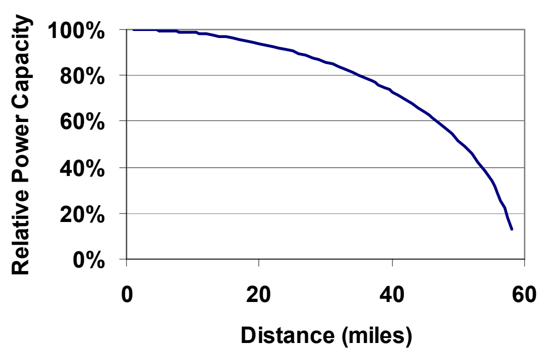

Figure 8 – Capacity of a typical 345 kV XLPE-insulated ac cable available for real power transmission.

Because the capacitance of a dc cable does not pass any continuous current, there is no need for any compensation. The only impact of the cable capacitance is on the dynamic response and disturbance recovery of the dc system, where increased dc cable capacitance may slightly slow fault recovery rates.

The physics of cable insulation for ac and HVDC are quite different, thus it is not correct to compare ac and HVDC cable insulation requirements simply by equating the peak sinusoidal voltage of the ac application with the maximum continuous operating voltage of HVDC. Lower-cost solid-dielectric (cross-linked polyethylene, XLPE) cables have been proven up through 500 kV ac. At this time, XLPE cables have been proven only up through 350 kV dc. Higher dc voltages require an oil-filled or mass-impregnated cable design, which is generally more costly.

The skin effect has an even more significant impact on ac cable resistance than overhead conductor resistance. Overhead conductors typically have a less-conductive core for tensile strength (steel, high strength aluminum allow, or composite fiber), surrounded by high conductivity aluminum strands (e.g., Aluminum Conductor, Steel Reinforced, ACSR). Underground and undersea cables typically have highly conductive material used for all of the conductor. In the case of dc, the entire solid cable conductor cross-section is available for the direct current, but only the high-conductivity strands carry significant current in the overhead conductor. For ac, the current is concentrated in the outer area in either case. The net result is that the difference between ac and dc resistance is more substantial for a solid underground or undersea cable, compared to an overhead cable with a low-conductivity core.

All of these factors considered, HVDC cables have much lower per-mile costs relative to an ac cable of the same capacity, with its required compensation equipment. In some cases, the HVDC cable costs may be one-third to one-fourth the per-mile costs of the equivalent ac cable system, not including converter station costs.

3.4. Power Losses

As described in Sections 3.2 and 3.3, the effective resistance is less for a given conductor carrying alternating current compared to the same conductor carrying an equal amount of direct current. Line loss comparisons are complicated by the different design considerations for ac and HVDC. 345-kV ac lines typically use two conductors per phase in a bundle configuration, in order to reduce electric field gradients and the production of corona. Corona generates audible noise, electromagnetic interference, and energy losses. HVDC lines have different corona characteristics because the static voltage of the line develops a cloud of charges that effectively decreases electric field gradients. Because minimum ac conductor sizes are governed by corona, that are not related to current loading, ac lines are often designed and operated with a lower current density than dc lines. Thus, an HVDC line may have higher or lower loss than a comparable ac line, not considering conversion losses discussed below. This depends on the specific design. In general, however, HVDC line designs typically generate less power loss, per mile at a given power flow, than do ac lines.

HVDC, however, has substantial conversion losses. A conventional HVDC system has a loss at rated capacity of approximately 0.7% at each terminal. Exclusive of line losses, the end-to-end losses equal 1.4% of the transmitted power at rating. Voltage-source converter HVDC has much greater converter loss. In testimony to the Connecticut Siting Council, ABB, the leading vendor of VSC-HVDC, claimed end-to-end converter losses to be 3.49%[2], or 2.5 times that of conventional HVDC. In comparison, the terminal losses for an ac line are virtually zero.

There is a breakeven distance where the incremental converter losses of HVDC transmission are offset by the loss savings of the HVDC line itself.

4. SYSTEM PLANNING AND INTEGRATION CONSIDERATIONS

The characteristics of HVDC transmission are decisively different from ac transmission. Accordingly, there are a number of unique considerations involved in the planning and integration of HVDC transmission into an ac network.

4.1. Power-Flow Control

4.1.1. Steady-State Real Power Flow

As stated previously, the flow of real power through an HVDC line, under normal conditions, is precisely controllable and independent of the frequency and phase angles of the ac systems to which the HVDC system interconnects. In many applications, this can be a distinct advantage, such as:

- Ties between independent systems of different nominal frequencies
- Ties between independent systems of the same nominal frequency, but which are not synchronized.
- Ties between operating systems, for which precise flow control is desired for commercial or regulatory reasons.

Within a transmission system, the inherent tendency for an HVDC system to stay fixed at an ordered power flow can sometimes be detrimental. For example, in an ac transmission network, the trip-out of one transmission line causes the phase angle at the “sending” bus to naturally advance, and the phase angle at the “receiving” bus to naturally retard. As a result, the power flow from the generation resources to the loads automatically re-route over the remaining lines of the network according to the impedances and configurations of the various lines. As part of the transmission planning process, additional capacity is designed into ac transmission lines to accommodate power-flow shifts resulting from line outages and other contingencies. In addition, the thermal time constants of lines and other ac equipment allow ample short-term overload capability, giving system operators time to return tripped lines to service, or make other adjustments to the system (e.g., adjusting generation dispatch) to return line flows below their continuous ratings.

[2] ABB, Inc., Testimony before the Connecticut Siting Council in the matter of Docket 272, December 15, 2004.

If a HVDC line is substituted for ac lines, and no special provisions are made, the flow over the HVDC line will remain fixed when an ac line is tripped. Thus, the power flow "pickup" of other ac lines will be increased because the HVDC line is not contributing to the redistribution of the power transmission required between sources and loads. This requires either reinforcing the ac lines, or implementing a "special protection scheme" as described later in Section 4.1.3.

4.1.2. Dynamic Power Flows

During a fault, depression of system voltage reduces power flow out of the system's generators. Because their turbines continue to drive the generators, the power input from the turbine goes into the rotational inertia of the turbine-generator masses, causing them to accelerate. This advances the voltage phase angle at the generation-rich areas of the system. When the fault clears, flows over ac lines are greatly increased because of the large phase angle differences between generation-rich areas and load areas. This extra power flow extracts the extra rotational energy of the generators, and causes them to slow down. Power flows in the system will oscillate for a number of seconds after disturbances. In some systems, particularly the spread-out systems in the Western US, there is a tendency for these oscillations to grow, and reach the point where the system might break apart if it were not for special damping controls.

During a fault, power flow over an HVDC system may be reduced greatly, or collapse altogether, depending on the severity of the fault and whether it affects the rectifier or inverter. Faults near the inverter tend to have the most severe impact. Even a remote fault causing an abrupt voltage drop of 10% can cause a "commutation failure" of a conventional HVDC system, which results in a temporary interruption of power flow (few tenths of a second). When an ac fault is cleared, the HVDC system power does not instantly return to its ordered power flow. There is time required to execute a recovery of power flow. The recovery time varies from application to application, depending on ac system strength at the inverter and rectifier terminals, and whether the dc line is a cable having a large capacitance requiring re-charge. This recovery time ranges from about 150 ms to 500 ms.

Faults are usually cleared by tripping a system component, such as a line. In addition to the power-flow pickup required by loss of the line and extra flow due to the acceleration of generators, the ac system must also compensate for the difference between an HVDC line's ordered power flow and the actual value during recovery. Power flows and limitation of phase angle swings during this dynamic post-fault period are critical to the system, as insufficient transmission capacity can result in phase angle differences exceeding the point of stability.

4.1.3. Special Protection Systems and Modulation Schemes

In the longer-term, system operators could adjust power flow on an HVDC line such that the line participates in the redistribution of power flows, in order to mitigate overloads in the ac network. Operator intervention, however, is not desirable. System failures and outages place a great deal of stressful, immediate workload on system operators. Manual adjustment of HVDC line flows would substantially add to this burden, increasing the risk of making mistakes, and thus jeopardizing system security. Such action also requires a fully functioning SCADA (supervisory control and data acquisition) system; thus dependency on such a scheme increases risks to system security brought on by SCADA outages or misoperations. Present NERC planning criteria requires that post-contingency flows must be within the short-term capacity of all network components, without any re-dispatch or manual intervention by system operators. Thus, manual readjustment of HVDC line flows cannot be considered in determining the required ratings of ac lines subject to increased flow because of the HVDC line's inability to contribute flow pickup.

Automated readjustment of power flows is also possible, based on inputs of ac line flows or by measurements of voltage phase angles at the terminating buses. Hypothetically, the controls of an HVDC line could be programmed to provide steady-state flow characteristics that emulate the ac line power flow laws. Such schemes are complex and are reliant on reliable communications infrastructure. For example, flows from multiple ac lines distant from the HVDC line might need to be monitored, and telemetered to the HVDC control point. Alternatively, in a scheme emulating ac flow laws, the ac phase angles from both terminals of the HVDC line need to be telemetered to the control point so that HVDC power flow could be made proportional to phase angle difference. Phase angle measurements require a precise time reference, usually provided by the GPS system. In such a scheme, the security of the transmission grid could be made dependent on a system of satellites in outer space. All of these schemes are characterized by ISO-NE rules as "special protection schemes"(SPS). There are numerous rules and restrictions on the use of SPS, in recognition of their posing a vulnerability of system insecurity. None of these control approaches are proven, nor have they ever been employed to mimic the robust, near instantaneous, self-equalizing characteristics of AC systems.

Even with a perfect SPS control scheme, there are restrictions on the ability to control or increase HVDC power flow. Incremental capacity of an HVDC line tends to be more expensive than incremental capacity of an ac line (more massive power electronics in the case of HVDC versus a slightly larger conductor size in the case of ac). Therefore, HVDC systems tend to be specified with a continuous rating equal to the maximum normal power flow. Short-term overload capability can be obtained in an HVDC system design at a lower incremental cost than continuous HVDC capacity, but at a much greater cost than incremental short-term ac line capacity. This short-term capacity can be applied to manage post-contingency power-flow redistribution. However, if the system outage is extended, other measures will need to be taken to mitigate network overloads when the HVDC system is at the end of its overload time limitation.

An SPS does not change the fact that HVDC systems require a recovery period after a fault. Thus, an HVDC system does not contribute to first-swing transient stability of the system, and may even detract from meeting that stability requirement.

If an ac system is poorly damped, and susceptible to a dynamic instability that occurs when angle oscillations grow, an HVDC system can be a very effective mitigant. In this time period, seconds after a fault, HVDC flow is fully recovered and fully controllable. Using local measurements of instantaneous frequency only, HVDC power flow can be modulated to provide damping of power swings. A very small amount of HVDC flow variation can be highly effective. Modulation schemes are used HVDC systems in the Western U.S., and have been effective in increasing the loadability of the ac network by reducing dynamic stability limitations on flow. This type of dynamic stability problem is not characteristic of the Southern New England power system, however.

4.2. System Strength

4.2.1. Conventional HVDC Systems

As stated previously, a conventional HVDC system is reliant on the strength of the ac systems to which it is connected. Inadequate system strength can lead to a number of operational and design problems, including:

- Inability to commutate current in the conversion process
- Instability of controls
- Excessive variation in ac system voltage due to HVDC flow changes, including potential for severe ac overvoltages
- Low-order harmonic resonances, with contributions to overvoltages and undesirable system interactions and instabilities.
- Increased tendency to collapse HVDC power transfer due to small ac voltage disturbances.
- Increased time required to recover from disturbances.

A general rule of thumb is that if the short-circuit capacity of the ac systems, divided by the HVDC system rated power, (short circuit ratio) is greater than three, then HVDC performance is not significantly compromised by ac system strength. The ac system short-circuit capacities should include any contingency situations within planning criteria, and all expected system configurations and generator commitments. As the short-circuit ratio is reduced toward two, system issues become increasingly more significant. Operation of an HVDC system with a short-circuit ratio less than two is inadvisable.

During an extreme contingency, when a system is breaking apart, the short-circuit strength of the ac system will decrease below values considered in normal planning. During breakup, the HVDC system can behave unpredictably due to unplanned system weakness, potentially causing damaging overvoltages or pulsations of power that mechanically damage generators or other equipment. Thus, in addition to a blackout, a system can be confronted with physically damaged ac and HVDC equipment that cannot be restored to service without long delays.

A conventional HVDC system cannot be used early in the system restoration following a blackout. The HVDC system can only be brought on line when there is sufficient generation and ac transmission lines already in service to provide adequate short-circuit strength.

4.2.2. VSC-HVDC

VSC-HVDC systems can, ideally, operate without any ac system short-circuit strength. The largest vendor of these systems claims the ability to black-start a system without operating generation at the inverter end. However, VSC-HVDC systems are normally controlled as current sources, and a current source is prone to instability in excessively weak conditions. The solution to this is to shift the control architecture to act as a voltage source in such conditions. The control needs to know, however, when such a shift is necessary. Available literature does not disclose how this is accomplished, or if the low short-circuit condition can be determined autonomously by the VSC-HVDC control without external information indicating the status of the ac network. If such external information is needed, then it would necessarily be considered a special protection scheme.

4.3. Power Quality

4.3.1. Harmonics

As stated earlier, the conversion process from ac to dc, and vice versa, generates harmonic currents. Harmonics distort voltages and currents, and are considered to be a "pollution" of the power system. Although harmonics are generated by loads and other power-system devices, HVDC systems are uniquely concentrated sources.

The potential impact of excess harmonics can be summarized as follows:

- Heating of motors, transformers, and other equipment
- Overstress of capacitor units, causing premature failure and fuse operations
- Misoperations of controls, clocks, and other devices sensing voltage zero-crossings as a reference to time or frequency
- Inductive interference with telephone systems

IEEE Standard 519 places the responsibility for control of voltage distortion on utilities. HVDC system specifications typically require that the HVDC system design have adequate filtering to meet voltage distortion requirements at least as stringent as given by this standard. Control of inductive interference of telephone systems, however, requires control of harmonic currents from HVDC systems. Harmonic currents escaping into the ac network create a magnetic field which can couple induced voltages onto telephone cables located hundreds or even thousands of feet away from the ac lines, as illustrated in Figure 9. Some portion of these voltages appear across the telephone set, creating a hum that can make the telephone circuit unusable. This can be a significant issue in urban and dense suburban areas where transmission lines may run in close parallel proximity to telephone lines. Specialized studies may be needed to determine the allowable harmonic current escaping the filtering process into the ac system. Likewise, dc-side harmonic current specifications are needed for overhead HVDC lines to avoid telephone interference.

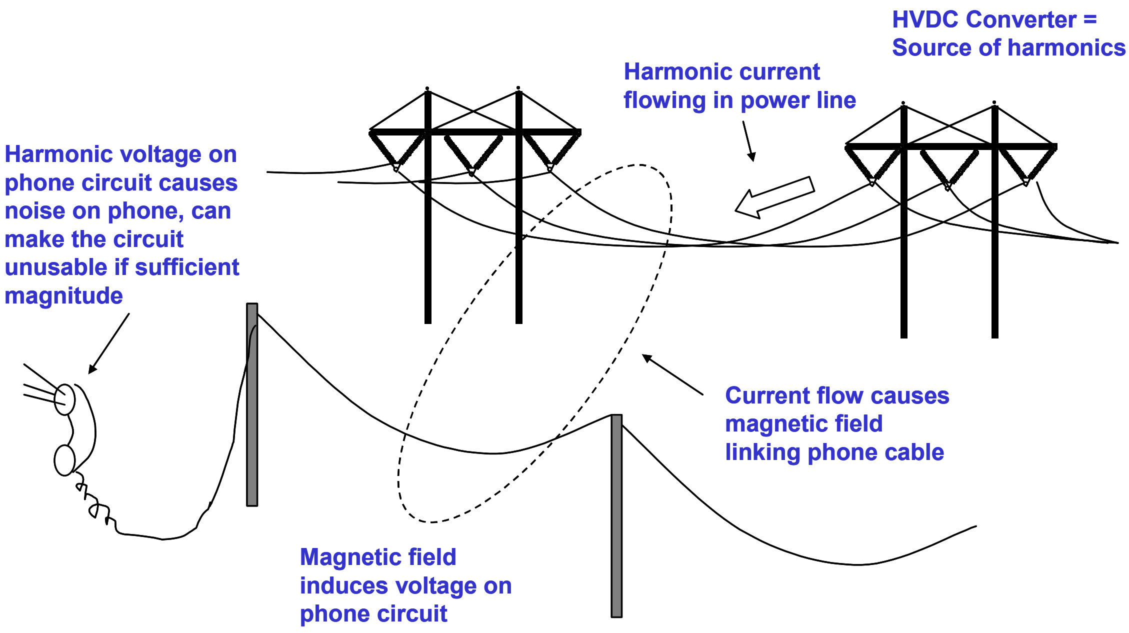

Figure 9 – Illustration of telephone interference caused by harmonic current flow on transmission lines.

Significant increases in system distortion, and telephone interference problems, can be avoided by proper design of harmonic filtering in the HVDC system design to meet properly defined performance specifications. The last is the key; significant effort is needed by the procuring utility to adequately determine harmonic performance specifications, particularly those involving telephone interference. Telephone interference is an issue that cannot be adequately covered by generic specifications; project-specific performance requirements are the appropriate means to address this issue. Project-specific requirements are defined by detailed pre-specification studies. These studies require significant lead time, increasing the project cycle time.

4.3.2. Overvoltages

A conventional HVDC system requires a large amount of capacitor and filter banks to be installed to meet reactive demand when the HVDC system is functioning. A disturbance, such as a fault at the remote terminal, can cause the HVDC system to shut down or reduce power level such that the reactive demand is mostly eliminated. The excess reactive power generated by the reactive compensation will drive up system voltage. Switching off the un-needed compensation banks takes from 50 to 100 milliseconds; in the meantime, utility and customer equipment is exposed to the elevated voltage. Switching off compensation banks is usually a last-resort action by the HVDC station control logic, because once switched off, the banks have to be discharged before being switched back on. This can limit the ability of the HVDC system to recover power transfer to levels where the banks are again needed.

The degree of overvoltage caused by "load rejection" of an HVDC system depends on the strength of the ac system. If sufficiently strong, these overvoltages are modest and tolerable. In weaker ac systems, this overvoltage issue becomes a major design issue.

Because VSC-HVDC systems do not need large filter banks, and the converters are a controlled reactive source, this load rejection overvoltage issue is not relevant to this HVDC technology.

4.4. System Interactions

An HVDC system is a controlled device that affects the voltages and currents in an ac power system. In this manner, the HVDC control can interact with other system equipment, particularly turbine-generators, and control systems of other devices and systems. Examples of other controlled devices vulnerable to interaction are other HVDC systems and FACTS devices. It is possible for these interactions to have undesired consequences, in the extreme leading to system misoperation, control instability, and equipment failure. It is important that the potential for interactions with existing equipment and systems be properly investigated during HVDC system design phase, so that adequate safeguards and protections can be implemented. The major complication, however, is that for any future addition of vulnerable equipment that is electrically "close" to the HVDC system, interaction needs to be studied in the future. This requires much more sophisticated models of the HVDC system than the dynamic simulations models normally provided by the vendors for system planning studies. This is not an insurmountable issue, but one requiring future diligence throughout the life of the HVDC system.

One interaction of particular significance, proven to involve HVDC systems, is called subsynchronous torsional interaction (SSTI). Large turbine-generators have torsional modes of vibration where one part of the turbine-generator unit will twist with respect to another at a particular frequency that is below the synchronous frequency of the system. Such oscillations can be stimulated by any switching or fault event in the system. The torsional oscillation modes are poorly damped, meaning they take a long time to die out. When the generator oscillates at one of these modal frequencies, the voltage has a small amount of phase modulation. A nearby HVDC system can be affected by this phase modulation. Because the HVDC controls are not fast enough to keep the dc power perfectly constant during this modulation, there is a variation in the dc power at the same frequency. The phasing of this dc power variation can create a negative damping of the torsional oscillation; meaning that the oscillation can grow. This SSTI phenomenon is illustrated in Figure 10.

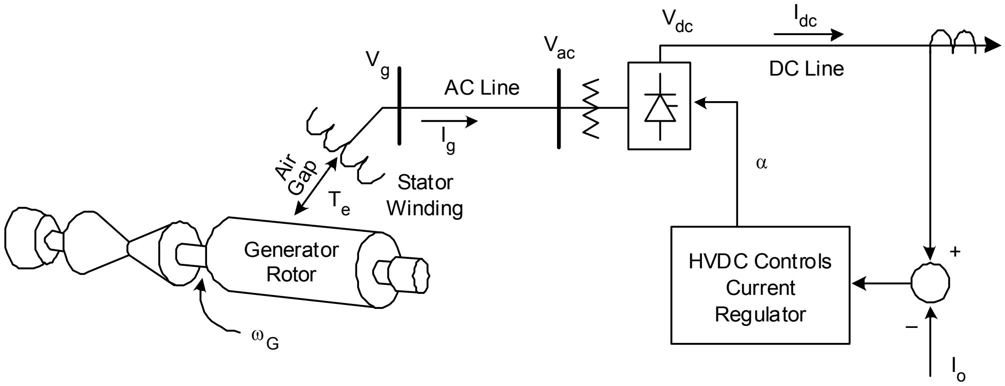

Figure 10 – Subsynchronous torsional interaction.

It is possible for this oscillation to grow to the point where the turbine-generator shaft can be sheared, destroying the machine. Generators have been severely damaged in at least two incidents involving negatively damped torsional oscillations.[3] Replacement of a generating unit's rotor can take more than a year; at great cost and impact on system generating reserves.

SSTI is a phenomenon that can be avoided by specific HVDC control design features. This should be backed-up with special torsional protection schemes applied to vulnerable turbine generators. While this is not an insurmountable problem, SSTI is an example of the complexities of HVDC integration into a system, and the potential ramifications of incorrectly doing so.

4.5. Reliability

Overhead transmission lines are rarely taken out of service for planned maintenance, as there are a number of work practices allowing much maintenance to be performed "hot" with the line in service. Ac and HVDC lines are subject to infrequent unplanned, or "forced" outage for various line related reasons, including severe weather (e.g., tornados, severe icing), tower failure, and insulator failure.

Outage of an ac line due to substation issues is quite rare. Thus, the overall availability of ac lines is very high. Ac transmission lines rarely need to be taken out of service to accomplish planned maintenance of line termination (substation) equipment, and forced (unplanned) line outages due to substation problems are rare. This is due to the redundancy in standard ac substation designs, and due to the inherent simplicity of the equipment critical to a line.

The availability of HVDC lines, however, is dependent on the availability of the converter station equipment. This equipment is complex, with many subsystems, and requires routine off-line maintenance. HVDC systems typically have a planned maintenance period of several days

[3] These failure events did not involve HVDC system, but did involve a related phenomenon. Several events involving HVDC have occurred, but in each case, either the turbine generator or HVDC were shut down prior to major damage.

to one-week in duration, performed on an annual basis. In addition, forced outages are much more frequently caused by converter equipment failures and misoperations compared to outages of ac lines caused by substation equipment. As a result, the unavailability rates of HVDC systems is typically on the order of 2% to 3% of the time. Of this, the majority are planned outages, but a significant amount are forced (unplanned) outages which may occur at a critical time for system operations and security.

4.6. Power Transfer Capability

The maximum rated capacity of HVDC transmission is markedly different for conventional HVDC and VSC-HVDC. Conventional HVDC is a mature technology that has been applied to systems of very large power transfer capacity, arguably much more than is feasibly transmitted by a single ac line. The Xianjiaba-Shanghai HVDC system now under construction in China will have a rated capacity of 6400 MW, with the voltage between poles (equivalent to phases in an ac system) of 1.6 million volts. These ultra-large projects are overhead lines. Conventional HVDC has been used for undersea cables of up to 1400 MW capacity, with a 3000 MW link planned for construction.

VSC-HVDC is an emerging technology that has been applied for lower-capacity intertie requirements. The Estlink tie, between Estonia and Finland, represents the maximum capacity of in-service VSC-HVDC systems, with a rating of 350 MW. A 400 MW VSC-HVDC cable across San Francisco Bay is now under construction. Literature from one of the vendors of VSC-HVDC systems, ABB, indicates that the technology can feasibly be extended to lines with capacities of 1140 MW for underground cables using a monopolar configuration, and 2277 MW for overhead lines using a bipolar configuration[4]. VSC-HVDC lines of this level of capacity, however, have never been built.

4.7. Transmission Line Capacity Upgrades

Increase of the power capacity of a transmission line can be accomplished, with significant difficulty, by either increasing the operating voltage or by increasing the current capability. These upgrades usually require extensive modifications to the transmission line itself, unless provisions for future upgrade are explicitly built into the original line design. These provisions increase the initial cost. Thus, the carrying charges for these provisions must be borne for the economic life of the system, including the initial years when the increased capacity is not yet needed. In the case of HVDC systems, substantial converter station modifications or additions are required as well as modifications of the overhead line or underground cable.

[4] M. Bahrman, *op. cit.*

4.7.1. Overhead Line Capacity Upgrade

Increased overhead HVDC and ac line voltage requires both an increase in the length of line insulator strings and increased clearances between the line and supporting structure as well as the line and ground. Unless line supporting structures were originally designed with excess dimensions, significant voltage upgrade at a future time is generally infeasible without complete rebuild of the line. A further complication is that ac lines are always designed and operated for widely-separated standard voltage levels that are used in a particular system. In New England, 230 kV and 345 kV are used for bulk transmission; ac lines are not designed and operated at voltages customized for the particular application. This facilitates interconnection with other lines in the future. HVDC systems, however, tend to be designed as "closed" systems, with no interconnections to other lines on the dc side. Voltages, therefore, are customized for the application, and an increase in voltage from, say, 400 kV to 500 kV is technically feasible.

For both HVDC and ac overhead transmission lines, increased current capacity may require increasing the conductor size. Increased conductor size generally implies increased conductor weight and tensions; thus the line structures need to be able to support the larger conductor size while meeting applicable safety codes. In some cases, structural upgrades might be achievable by retrofit reinforcements of line structures. In general, however, a line must be built with extra initial structural margin to be able to accommodate a future conductor size upgrade. An alternative now available, however, is the use of new conductor materials (e.g., aluminum conductor – composite reinforced) that can allow higher currents without increasing structural loading or sag clearance requirements.

4.7.2. Underground Cable Capacity Upgrade

The voltage ratings of underground ac or HVDC cables cannot be upgraded without replacement of the entire cable. Thus, voltage upgrade of underground cable transmission systems is generally not feasible, unless the original cable had the capability for the final voltage level and was under-applied at the initial voltage level. Current ratings of solid dielectric cables cannot be increased, but ratings of pipe-type cables can be increased by providing or increasing forced cooling of the cable.

4.7.3. Upgrade of Line Terminal Capacity

By and large, the power capacity upgradeability of ac and HVDC <u>lines</u> is similarly constrained.. Ac and HVDC transmission <u>system</u> upgradeability, however, is substantially different, with the difference in the required changes in line terminal equipment. Ac line terminal capacity upgrades tend to be simple. In some cases, no modifications of substation equipment is needed to support an upgraded ac line capacity. In other cases, the modifications are relatively limited, such as replacing circuit breakers or increasing bus bar size.

Increases in HVDC system capacity, however, requires replacement, major modifications, or major additions to the converter stations. HVDC system capacity increases are generally accomplished by either adding another converter in parallel, to increase current rating, or another converter in series, to increase voltage rating. Either upgrade requires a commensurate increase in the amount of reactive compensation, harmonic filtering and cooling equipment required. Essentially, the upgrade is equivalent to adding an additional converter station. It is generally not economically feasible to make small increases in HVDC converter terminal rating. For this reason, HVDC system uprates have historically involved substantial increments of system capacity.

4.8. System Configuration Modifications

There are substantial differences in the flexibility afforded by ac and HVDC lines to accommodate future system expansion needs. AC transmission lines can be easily tapped, branched off, or extended by adding a new substation along their route. Tapping or extending an HVDC line is far more complicated than is the case for an AC line. These issues greatly decrease the practicality and increase the expense of future system expansion using an HVDC line. While such future expansion may be unlikely for HVDC lines interconnecting different systems, it is a great impediment to using HVDC as a backbone transmission means <u>within</u> a system.

4.8.1. Line Tapping for Load Support

Often, load growth in an area can often be supported by tapping an existing ac transmission line passing through the area. At this tap, a new substation is installed that reinforces the underlying system. Other than protective relay changes, nothing has to be changed at the original terminals of the ac line to accommodate the new need, as long as the power flows are within the capacity limitations. For example, CL&P is now in the process of constructing or has recently completed construction of three 345/115-kV autotransformer installations (Barbour Hill in South Windsor, Killingly, and Haddam). This efficient expansion of the CL&P network was made possible by tapping into nearby existing 345-kV transmission lines to serve local area load. If this option were not available, CL&P would have had to make extensive improvements to its 115-kV system, at greater cost and with more environmental impacts.

Tapping an HVDC line would be vastly more complicated, expensive, and may potentially compromise bulk transmission system security. Instead of a simple substation with power transformer, an HVDC line tap requires construction of an HVDC converter station, creating what is called a “multi-terminal HVDC system” (i.e., one with more than two terminals). Almost all HVDC systems have been constructed as two-terminal systems, as was previously discussed in Section 2.3.1. There have been only a very few multi-terminal HVDC systems ever built in the entire world. Adding terminals to an existing HVDC sytem requires substantial modification of the control systems at the existing terminals, with substantially increased complexity, in order to provide the necessary control coordination. Extensive system studies are required to integrate the new converter station to the ac and HVDC systems.

Usually, substations added along a major transmission line for local reinforcement require a capacity much less than that of the line. For conventional multi-terminal HVDC technology, the limited experience of the industry has shown that terminals with a power rating significantly smaller than that of the system's main terminals degrade system performance and potentially compromise system reliability. These terminals tend to allow small disturbances in the ac system near the terminals to cause major disruptions of power flow in the HVDC system overall. Also, the recovery of the HVDC system from disturbances may have to be slowed to accommodate the poor dynamic response capabilities of the small terminals, particularly if the ac system to which the small terminal is connected, is "weak".

A weak system has the tendency for larger-than-normal voltage change for a given change in load. By nature, a load area needing reinforcement is likely to have a weak system. It should also be noted that conventional HVDC does not provide any strengthening of the ac systems to which it connects, from the standpoint of voltage sensitivity. This is in contrast to a new substation added to an ac transmission line to serve local load; as such a substation substantially strengthens the local system. Integrating an HVDC system into a weak ac system presents numerous major technical challenges, including temporary overvoltages, low-order harmonic resonances, and control instability. Therefore, tapping a conventional HVDC system to serve local load would, at best, be technically challenging as well as extremely expensive.

Theoretically, a tap could be added to a VSC-HVDC system to serve local load, and avoid some of the technical issues complicating a tap of a conventional HVDC system. A VSC-HVDC converter can provide reactive power support to a local system and help stabilize voltage fluctuations. However, there has never been a multi-terminal VSC-HVDC system constructed anywhere in the world. The application of VSC-HVDC technology to multi-terminal systems is totally hypothetical at this time.

4.8.2. Line Tapping for Generator Interconnection

Another reason that ac transmission lines are frequently tapped is to provide a means to interconnect new generation plants built along the line's path. To provide such interconnection via an HVDC line would require construction of an entire converter station, as well as a conversion of the whole HVDC control system to accommodate multi-terminal operation. The costs for such an installation, along with the numerous specialized studies required for system integration, would be an order of magnitude greater than required to install a substation for interconnection to an ac transmission line.

These additional costs would place generators at a competitive disadvantage and hinder the development of a competitive generation market. Generators would necessarily bear the capital and operating costs of the interconnecting HVDC converter terminals in order for their power to be delivered to the grid via the HVDC system. The additional cost of generation interconnection (or the threat of such additional cost, given that no formal determination could be made regarding the need for converters until a generator was proposed) could result in no new generation of any significant size being proposed along or near the line route.

Embedding an HVDC facility within an AC system would hinder the development of a competitive market due to high generator interconnection costs. Generators would need to pay for and utilize DC converter stations in order for their power to be delivered to the grid via the HVDC system. These additional costs would place generators at a competitive disadvantage and hinder the development of a competitive generation market. The additional cost of generation interconnection could result in no new generation of any significant size being proposed along or near the line's route.

5. TYPICAL HVDC APPLICATION SCENARIOS

There are limitations to the usage of HVDC transmission, but there are also great advantages for certain applications. For almost all HVDC systems built around the world, there either was no viable ac alternative to meet the functional needs, or the HVDC system was economically preferable due to long distances involved.

In this section, the various situations and requirements driving use of the HVDC solutions in example projects are discussed.

5.1. System Interconnection

5.1.1. Asynchronous Systems

Various regions of the world, for historical reasons, use either 50 Hz or 60 Hz operating frequencies. In some places, systems with these two operating frequencies adjoin each other. HVDC provides the only feasible means to interconnect these asynchronous systems, in order to interchange power for economic or system security reasons.

There are also regions of the same operating frequency which are not synchronized with each other. North America has four major systems which are not synchronized with each other. These are the:

- Eastern Interconnection, running from Florida to Saskatchewan, and eastern New Mexico to the Canadian Maritimes, with the exception of Quebec and Texas.
- Western Interconnection, running from the foothills of the Rockies to the Pacific Ocean.
- Texas, and
- Quebec

These systems cannot be feasibly connected to each other by conventional ac lines, unless the interconnecting ac infrastructure had enough capacity to hold the respective systems together in synchronism. Therefore, until recently, the only feasible means to provide power transfer capacity between these separate systems was with HVDC. An example of this application is the back-to-back HVDC interconnection at Cheateauguay, Quebec, that interconnects the Quebec system and the New York system of the Eastern Interconnection.

A new ac technology, called the Variable Frequency Transformer (VFT), has been introduced which does allow asynchronous interconnection of ac systems without using HVDC technology. A VFT has been installed at Langlois Station in Quebec to also provide interconnection to New York. A VFT is a substantial piece of apparatus and has a cost in the same general range as an HVDC back-to-back converter station.

5.1.2. Dynamically Constrained Systems

Because ac power transfer is limited by the inductive reactance of the lines. At very long lengths, many hundreds of miles, the effective capacity of an ac line is substantially reduced from the thermal limits of its conductors, due to stability constraints. HVDC transmission is not constrained significantly in capacity by virtue of its length. Thus, there are HVDC transmission applications where ac is not a very feasible alternative, due to length. A recently announced 6,400 MW HVDC transmission line project between Xiangjiaba and Shanghai in China, a distance of 1286 miles, is an excellent example of this application.

It can be difficult to maintain the stability of generating units that are clustered in isolated areas, far from the load. HVDC provides a means of connecting these generator stations with the system load without the stability constraints of ac. This is a particularly good option for remote large-scale hydro-electric units, which are very tolerant of the wide frequency variations that might occur in a remote generation subsystem during a grid disturbance. Manitoba Hydro uses HVDC for such an application to interconnect hydro generation in the far northern portion of the province with the more inhabited areas of the southern portion.

Ac systems having very long transmission lines tend to have poorly damped dynamic oscillations. The damping tends to decrease when power transfer levels are high. As a result, power transmission in such areas can be constrained by dynamic stability issues. HVDC lines in rough parallel with the dynamically-constrained lines can provide damping of the dynamic oscillations, as previously discussed in Section 4.1.3, and thus HVDC transmission can increase the power capacity of ac lines, as well as transmit power over the HVDC line. Such a modulation scheme is partial justification for the Pacific HVDC Intertie between Oregon and Southern California.

5.1.3. Merchant Interconnections

As discussed in Section 2.1, the flow of power in an ac system cannot be easily controlled as it follows the rules of physics. Devices like complex phase-shifting transformers, variable-frequency transformers, and certain FACTS devices are infrequently used to control power flow.

Almost all transmission lines are owned by public or regulated utilities. There has been recent emergence of the concept of merchant transmission lines, owned by non-utility corporations and whose transmission capacity is sold on the market to power producers or load-serving utilities. Precise control of power flow is needed over merchant transmission lines to meet contractual obligations. Also, if a merchant transmission line interconnects separately-operated portions of the grid, controlled flow may also be necessary to meet rules and requirements of the system operators.

The only merchant transmission lines in the U.S. use HVDC, and these are the Cross-Sound Cable between Connecticut in the ISO-New England system and Long Island in the ISO-NY system, and the Neptune RTS system between New Jersey and Long Island.

5.2. Long Distance Transmission

5.2.1. Comparative Line Costs

As discussed in Section 3, HVDC lines tend to cost less than ac lines of equivalent capacity, on a per-mile basis exclusive of the converter stations. The converter stations, however, are a substantial cost. As illustrated in Figure 11, there is a breakeven distance where HVDC is simply the least-cost transmission alternative. This breakeven distance is very sensitive to relative costs, but is on the order of 300 to 600 miles of un-tapped length for an overhead line application.

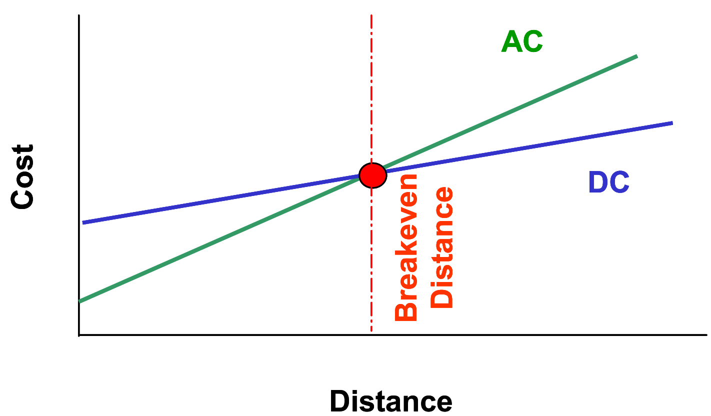

Figure 11 – Illustration of economic breakeven distance for HVDC

5.2.2. Undersea/Underground Cables

Because of the high cost of underground cable, and the larger differential between ac and dc cable costs, the economic breakeven distance between ac and HVDC for underground cable applications is much shorter than for overhead. This breakeven distance is on the order of 30 to 60 miles, depending on line capacity.

For underwater applications, shunt compensation of the large amount of ac cable charging capacitance at intermediate points is not feasible. Thus, ac transmission becomes technically infeasible for underwater applications having lengths on the order of 20 to 60 miles.

5.3. Urban Infeed

Addition of ac transmission lines, or new generating plants, tends to increase the magnitude of short-circuit currents possible on the system near the new additions. System components, particularly circuit breakers, have short-circuit current limits. These limits can be a major issue for tightly networked urban areas. Short-circuit levels present a major challenge to planning capacity additions to such areas, whether from generators outside of the urban area connected by new lines, or by adding generation within the urban area. HVDC can transmit power, but does not add significantly to short-circuit current levels. Thus, HVDC can be applied to import power to an urban area without costly upgrades of other equipment to meet short-circuit current requirements, upgrades that would be necessary if the power capacity were secured by other means. The advantages of HVDC for underground cables also supports the urban application. Conversely, the rather large space required for converter stations can be a disadvantage of HVDC. The Kingsnorth HVDC line in the UK, feeding into the London area, is an example of this application.

5.4. Plural Justifications

Typically, there is more than one reason supporting the application of HVDC. The Neptune RTS cable is an application where HVDC is technically necessary, due to the cable length, as well as being necessary because of the merchant status of the line. The Pacific HVDC Intertie is a very long line, justified economically by length, as well as a providing a means to dampen dynamic oscillations of the ac grid through use of HVDC power modulation.

5.5. North American HVDC System

There are 24 HVDC systems in all of North America, shown on the map in Figure 12, and listed in Table 1. Fifteen of these systems are back-to-back converters used to allow power transfer between the five major asynchronous grids in North America: Eastern Interconnection, Western Energy Coordinating Council (WECC), Hydro Quebec, Electric Reliability Council of Texas (ERCOT), and CFE (Mexico). With the exception of the Chateauguay converter station in Quebec and the Welsh converter station in Texas, all of these back-to-back systems are rated 350 MW or less.

Only nine projects are point-to-point HVDC transmission lines. For each project, the primary reason for application of HVDC is indicated.

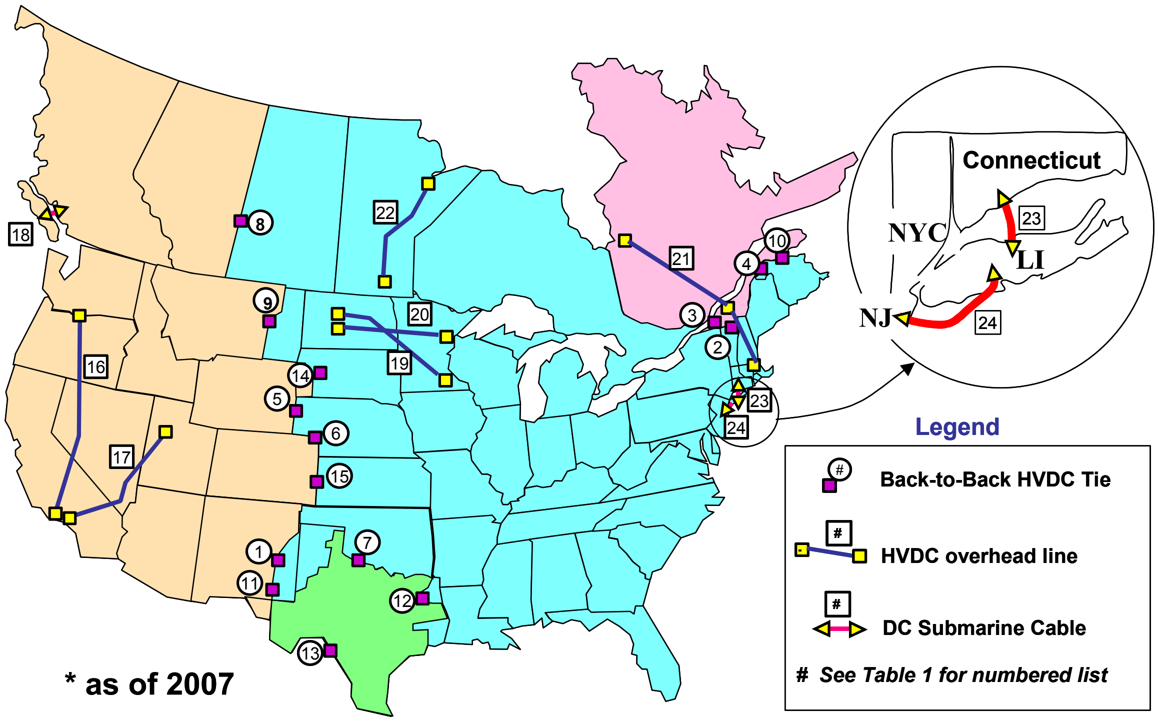

Figure 12 – Location of HVDC systems in North America.

Table 1
North American HVDC Systems

Key	Name	Rating (MW)	Reason for HVDC Application
1	Blackwater	200	Asynchronous Interconnection (Eastern-WECC)
2	Highgate	200	Asynchronous Interconnection (Eastern-HQ)
3	Chateauguay	1000	Asynchronous Interconnection (Eastern-HQ)
4	Eel River	320	Asynchronous Interconnection (Eastern-HQ)
5	Hamil	100	Asynchronous Interconnection (Eastern-WECC)
6	Virginia Smith	200	Asynchronous Interconnection (Eastern-WECC)
7	Oklaunion	200	Asynchronous Interconnection (Eastern-ERCOT)
8	Mc Neill	150	Asynchronous Interconnection (Eastern-WECC)
9	Miles City	200	Asynchronous Interconnection (Eastern-WECC)
10	Madawaska	350	Asynchronous Interconnection (Eastern-HQ)
11	Eddy County	200	Asynchronous Interconnection (Eastern-WECC)
12	Welsh	600	Asynchronous Interconnection (Eastern-ERCOT)
13	Eagle Pass*	36	Asynchronous Interconnection (ERCOT-CFE)
14	Rapid City	200	Asynchronous Interconnection (Eastern-WECC)
15	Lamar	210	Asynchronous Interconnection (Eastern-WECC)
16	Pacific HVDC Intertie	3100	Long distance, dynamic stabilization
17	Intermountain Power Project	1920	Long distance, remote generation (coal by wire)
18	Vancouver Island Cable	682	Undersea cable
19	CPA/UPA	1000	Long distance, remote generation (coal by wire)
20	Square Butte	500	Long distance, remote generation (coal by wire)
21	HQ-New England	2000	Long distance, asynchronous interconnection
22	Nelson River	3668	Long distance, remote hydro generation
23	Cross-Sound Cable*	330	Undersea cable
24	Neptune RTS	660	Undersea cable

*These systems use voltage-source converter technology (VSC-HVDC). All other systems listed use conventional system-commutated converter technology.

6. APPLICABILITY AS A NEEWS ALTERNATIVE

In the Southern New England Transmission Reliability Analysis, a number of options were developed to solve a number interrelated transmission issues. One option (Option E) proposed a 1,200 MW HVDC line from Millbury to Southington as a single solution to the Interstate and Connecticut East-West components of the transmission needs. The required line capacity, however, is recognized to be at the limits of practicality for VSC-HVDC, if this technology is to be applied[5].

Studies performed during the analysis have assessed the functional performance of Option E, and it has been determined to meet the established performance criteria. This section of the report takes a broader view; examining how this solution conforms to HVDC application precedents, and examines some of the technical issues that are outside of the normal scope of planning studies.

6.1. Application Conformance

In the half-century existence of HVDC, applications have tended to fall into the application categories discussed previously in Section 5. These proven application categories are compared with the proposed use of HVDC in Option E:

Asynchronous system – The transmission system into which Option E would be added is a heavily networked, and fully synchronized system. This application category bears no relevance to Option E.

Dynamically constrained system – The transmission system in Southern New England is constrained by thermal loading, voltage, and occasionally transient (first swing) stability. Transmission distances are not sufficiently long in this area for oscillatory damping issues to be of significant relevance.

Merchant transmission – The proposed transmission lines in the New England East-West Solution are all to be utility-owned and operated as a part of the backbone of the ISO-New England grid. They are not merchant transmission.

Long distance – All of the competing ac alternatives to Option E can be characterized as relatively short ac lines. If the transmission path of Option E was to be all underground, then it would be characterizable as a "long" underground system.

Urban infeed – The proposed Option E cannot be considered a classic urban infeed application. While there are some urban and suburban areas along the route, the line would also traverse extended distances of rural areas as well. While short-circuit current considerations are of some importance in this area, the short-circuit current provided by the alternative ac options can be accommodated without major equipment availability issues or widespread upgrade of existing equipment.

5 It has been assumed that VSC-HVDC is considered for NEEWS because of its ability to be applied for underground transmission. Therefore, feasible ranges of VSC-HVDC overhead line ratings were not considered pertinent.

The NEEWS project does not fall within any of the established reasons for using HVDC technology. Unless there were compelling technical or economic benefits to HVDC, an AC solution would typically be recommended for the problems NEEWS is trying to solve.

6.2. Short-Circuit Strength Considerations

An ac line contributes to short-circuit strength in the network, but an HVDC line does not. Previously discussed was the negative implication of this potential increase in component short-circuit withstand requirements. On the other hand, short-circuit strength indicates the "stiffness" of the system; the amount that voltage changes for a given load or reactive power change. Stiffness also plays a role in the frequencies of system resonances.

Southwest Connecticut has voltage stability issues. Addition of ac transmission, even in Central and Northern Connecticut helps stiffen the system overall, and makes a positive contribution to system strength in the affected areas. Selection of Option E does not provide this reinforcement; HVDC moves power but does not stiffen a system.

6.3. Contributions to Resonance Issues

During the planning of the Middletown-Norwalk transmission upgrade, there was considerable concern regarding resonant characteristics of the system when options with large amounts of ac cable were considered as options. Studies indicated potentially damaging temporary overvoltage conditions stimulated by system faults and switching.

Option E, if conventional HVDC is used, would require installing approximately 600 MVAR of shunt capacitor and harmonic filter banks at the Southington bus. This capacitance lowers the system resonant frequencies, and adds to the severity of impedance resonances, just as would the addition of large amounts of ac cable.

Figure 13 compares the system driving point impedance versus frequency at the Southington bus, comparing cases of the pre-NEEWS system (base case), with HVDC capacitors included, and with a line outage as well. This can also affect the buses in Southwest Connecticut, as well. Figure 14 is the driving point impedance plot at the Norwalk 345 kV ac bus, showing a downward shift in the first resonant frequency (plot maximum) toward the critical second harmonic frequency (120 Hz) associated with temporary overvoltage phenomena.

If VSC-HVDC is used, the required high-frequency harmonic filters would be much smaller, on the order of 100-200 MVAR. This amount is not likely to result in critical changes in the low-order resonance characteristics that had been associated with temporary overvoltages in Southwest Connecticut.

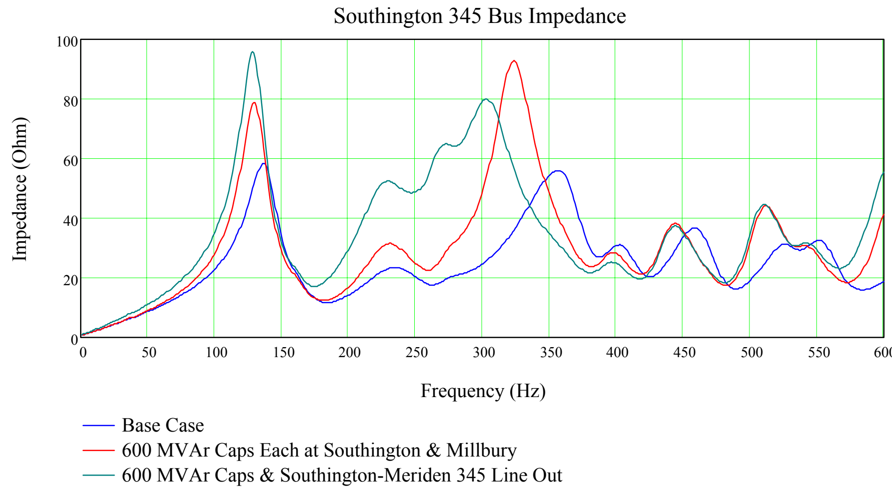

Figure 13 – Driving point impedance versus frequency at the Southington 345 kV bus.

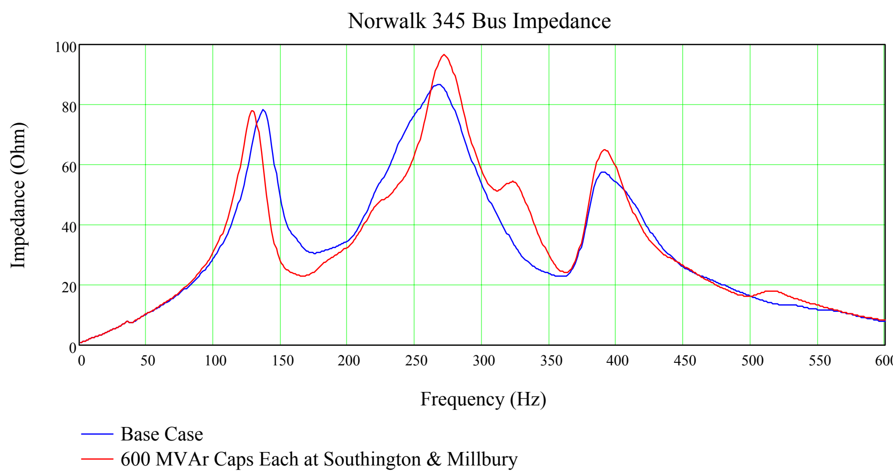

Figure 14 - Driving point impedance versus frequency at the Norwalk 345 kV bus.

7. CONCLUSIONS

HVDC transmission has a number of distinct technical advantages which are of great value in certain niche applications. Most of these advantages, such as providing asynchronous interconnection, limitation of short-circuit contribution, and facilitating use of long undersea cables, are not relevant to the NEEWS application. The reduction of short-circuit currents with an HVDC solution, compared to an equivalent ac transmission solution, has both positive and negative implications. The benefit of this short-circuit current reduction is avoidance or deferral of the need to upgrade equipment in locations where short-circuit currents approach the ratings of vulnerable equipment, particularly circuit breakers. This benefit may not have practical value until some time in the future when future generation additions and transmission upgrades increase short circuit levels to critical thresholds. On the other hand, decreased short-circuit strength in Central Connecticut tends to decrease system strength in Southwest Connecticut, increasing voltage stability and low-frequency resonance issues in that region.

On the other hand, HVDC transmission has a number of technical attributes that have a negative impact if this technology were to be applied to the NEEWS project. These include increased line terminal space requirements, converter station losses, lack of inherent power flow response to mitigate system contingencies, reduced short-term overload capability, risk of sub-synchronous torsional interaction with generating units, constrained future system expandability, aggravating system resonance issues, and reduced line reliability.

HVDC also has a great amount of complexity, which must be carefully managed during system specification, design, commissioning, and during any future system upgrades. Failure to adequately manage the complexities of system interactions can pose a further risk to system security and reliability.

The proposed HVDC line forming Option E of the New England East-West Solution is dissimilar to any established HVDC application niche. Weighing the very limited technical advantages of HVDC transmission technology for the NEEWS project application, against the significant technical disadvantages, there is no justification for favoring an HVDC solution over an ac solution unless the HVDC solution is substantially less costly. Costs are not within the scope of this paper, but it is reasonable to estimate that performing the solution with HVDC will, in fact, be much more costly than with ac transmission lines.

APPENDIX ITEM 3

COMPARATIVE ROUTING ANALYSIS OF OPTION A AND OPTION C-2

As described in the main text of this Solution Report, engineering analyses determined that a new 345-kV line constructed along Option A would provide greater system benefits at less cost less than Option C-2. However, because of the relatively small disparity in the cost of the two alternative routes, analyses of environmental and social factors were performed in order to further comparatively evaluate the two options. This comparative evaluation was performed by ENSR, Burns & McDonnell, and Phenix Environmental.

This section summarizes the results of the comparative evaluation of Options A and C-2. As described in the following text, based on these evaluations, the Option A route was found to have fewer environmental and social effects than the Option C-2 route

1.0 Option A

The following text and tables summarize the Option A facilities and route characteristics.

1.1 OPTION A FACILITIES

Option A would involve the development of a new 76.3 mile 345-kV line predominantly along existing ROWs in Massachusetts, Rhode Island, and Connecticut. Specifically, the new 345-kV line would extend from National Grid's Millbury Switching Station (located in the Town of Millbury, Massachusetts) to the West Farnum Substation (located in the Town of North Smithfield, Rhode Island). From the West Farnum Substation, the 345-kV line would extend west, past the Sherman Road Substation (located in the Town of Burrillville, Rhode Island), into Connecticut, first to CL&P's Lake Road Substation (located in the Town of Killingly), then from the Lake Road Substation to CL&P's Card Street Substation (located in the Town of Lebanon) and to Village Hill Rd. Junction in Lebanon (the 310 Loop).

In addition to the new 345-kV interconnection between the Millbury –West Farnum–Lake Road–Card Street Substations, Option A would require a reconductoring of the existing 345-kV line 347 between the Sherman Road Substation and the Rhode Island/Connecticut border (a distance of approximately 8.7 miles), and upgrading terminal equipment on the Sherman Road to the Blackstone 3361 line.

Overall, Option A would involve the construction and operation of approximately 37.7 miles of new 345-kV in Connecticut; 23.4 miles in Rhode Island, and 15.2 miles in Massachusetts.

1.2 OPTION A ROUTE CHARACTERISTICS

Option A would traverse portions of the following communities in each state:

- *Connecticut*: Lebanon, Columbia, Coventry, Mansfield, Chaplin, Hampton, Brooklyn, Putnam, Pomfret, Killingly, and Thompson.
- *Massachusetts*: Millbury, Sutton, Northridge, Uxbridge, and Millville.
- *Rhode Island*: Burrillville and North Smithfield.

The predominant characteristics of the Option A route in each state are summarized below.

Connecticut

ROW Configuration

In the 29.3 miles between the Card Street and Lake Road Substations, the new 345-kV line would be aligned primarily within CL&P's existing 150- to 360-foot-wide ROW. This ROW is presently occupied by the 330 circuit (a 345-kV line), mostly on wood-pole H-frames. Portions of the ROW also are occupied by 69-kV circuits (the 800 and 900) on a line of double circuit steel poles and 115-kV circuits (the 1505 and 1607) on both wood-pole H-frame structures. Within the existing ROW, the cleared width would need to be expanded 75 to 90 feet to accommodate the new line. An approximately 1.50-mile portion of the existing ROW through Mansfield Hollow (this includes the Mansfield Hollow Reservoir and State Park) is only 150 feet wide. In Mansfield Hollow Reservoir, the existing 330 Line is erected on steel monopoles. To accommodate the proposed new 345-kV transmission line on similar steel monopoles, CL&P would have to acquire an easement for an additional 150 feet of ROW. In the Mansfield Hollow State Park, the existing 330 line is erected on wood H-frames. To accommodate the proposed new 345-kV transmission line on similar wood-pole or steel H-frame structures, CL&P would have to acquire an easement for an additional 150 feet or ROW. Within sections of the existing ROW, the cleared width would need to be expanded 75 to 90 feet to accommodate the new line.

From the Lake Road Substation to the Connecticut/Rhode Island border, the Option A route would traverse approximately 7.5 miles and would be located entirely within CL&P's existing 250 to 400-foot-wide ROW. A single 345-kV line (the 347 circuit, on wood-pole H-frame structures) presently occupies this ROW.

Environmental Features

The Connecticut portion of the Option A ROW would traverse a total of approximately 36.8 miles. Land uses adjacent to this ROW vary from forested open space to urban/suburban areas near the communities of Brooklyn, Killingly, and Putnam. In general, however, the ROW traverses primarily rural areas.

Principal land use features along the route include the Airline State Park Trail, Hop River State Park Trail, Mansfield Hollow Dam and Reservoir, Mansfield Hollow State Park, Mansfield Hollow Wildlife Management Area, and the Natchaug State Forest. Major water resources along the Option A ROW include the Ten Mile River (Columbia); Hop River (Coventry), Mansfield Hollow Reservoir Mansfield); Natchaug River (Chaplin), Quinebaug River (Pomfret/Killingly/Putnam), and Five Mile River (Thompson). The ROW also crosses U.S. Routes 6 and 44 and Interstate 395, and Connecticut State Route 169, a National Scenic Byway.

Rhode Island

ROW Configuration

The Rhode Island component of Option A would extend from the Massachusetts border to the West Farnum Substation, and then from the West Farnum Substation, past the Sherman Road Substation, to the Rhode Island/Connecticut border, traversing portions of the towns of Burrillville and North Smithfield in Providence County.

From the Rhode Island/Connecticut state border to the Sherman Road Substation, the new 345-kV transmission line would be located within an existing ROW that generally varies in width from 300 to 500 feet. This ROW is presently occupied by the 345-kV 347 line on wood-pole H-frame structures. Along this segment, the new 345-kV transmission line would be installed on direct buried steel H-frame structures, similar in appearance to the 347 line structures. Within the existing ROW, the cleared width would need to be expanded by 85 to 95 feet to accommodate the new line.

Between the Sherman Road Substation and West Farnum Substation, the new 345-kV transmission line would be located entirely within an existing ROW that generally varies in width from 300 to 700 feet. This ROW is presently occupied by the 345 kV 328 line on wood-pole H-frame structures and, in some locations, the 115 kV B-23 line on single pole wood structures. Along this segment, the new 345 kV line would be installed on direct buried steel H-frame structures, similar in appearance to the 328 structures. Within the existing ROW, the cleared width would need to be expanded by 75 to 115 feet to accommodate the new line.

From West Farnum to the Massachusetts/Rhode Island border, the new 345-kV transmission line would be located within an existing ROW that generally varies in width from 250 to 270 feet. This ROW is presently occupied by the 115 kV S-171N and T172N lines in some locations and by the 115 kV Q-143S and R-144 lines in other locations. All of the 115 kV lines are installed on two-pole wood structures with the exception of R-144 which is installed on lattice steel towers. The new 345 kV line would be installed on direct buried steel H-frame structures, and in some ROW segments, it would replace an unused double circuit 69 kV lattice tower line. Within the existing ROW, the cleared width would need to be expanded at some locations by up to 135 feet.

Environmental Features

For the most part, the approximately 8.7 miles along the Option A ROW between the Rhode Island/Connecticut border and the Sherman Road Substation traverses primarily forested areas. The route also would cross the Clear River and Nipmuc River, as well as State Routes 100 and 96.

Similarly, the 9-mile ROW segment between the Sherman Road and West Farnum Substations is aligned through sparsely developed, forested areas. In Burrillville, the route would traverse approximately 0.8 mile across the Black Hut State Wildlife Management Area (which is managed by the Rhode Island Department of Environmental Management, Division of Fish and Wildlife), as well as Tucker Brook (a tributary of the Branch River). In North Smithfield, the route would traverse the Slatersville Reservoir, as well as portions of a cedar swamp near the West Farnum Substation. The Rhode Island state border–to-West Farnum Substation segment also would involve crossings of State Routes 7, 102 and 5, as well as local roads.

Between West Farnum Substation and the Rhode Island/Massachusetts border, the Option A route would generally traverse approximately 4.8 miles through urban/suburban areas characterized by a mix of land uses.

Massachusetts

ROW Configuration

Between the Millbury Switching Station and the Massachusetts/Rhode Island border, the Option A 345-kV transmission line would traverse portions of five municipalities for approximately 15.2 miles, within an existing 125-to-270-foot-wide transmission line ROW. The ROW is presently occupied by the 115-kV Q143N/Q143S and R-144 lines for the majority of the route and the 345-kV 302 line for a short distance. The existing 115- and 345-kV lines are typically installed on two pole wood structures with the exception of the R-144 line which is typically installed on lattice steel structures. The new 345-kV line would be installed on direct buried steel H-frame structures which, in most ROW segments, would replace an unused double circuit 69-kV lattice tower line. Within the existing ROW, the cleared width would need to be expanded at some locations by up to 115 feet.

Environmental Features

The Massachusetts portion of Option A would follow the existing transmission line ROW, which crosses the Blackstone River and passes by or through residential, commercial, and industrial land uses. For example, in the Town of Sutton, the ROW would be located near several residential subdivisions, and pass through portions of a gravel mining operation and a landfill. In Sutton, the route passes though Sutton State Forest. In the Town of Uxbridge, the route crosses Lackey Pond and crosses the Blackstone River twice. Prominent highways crossed along the Option A route include State Routes 122A, 146 (Worcester-Providence Turnpike), 16, and 146A.

1.3 OPTION A DATA SUMMARY TABLES

For the initial comparative evaluation of Option A (as well as Option C-2), ROW, environmental, and engineering data were compiled for each route segment (i.e., with a segment corresponding to the ROW between substations) based on the review and analysis of available Geographic Information Systems databases, maps, and aerial photographs.[1] For Option A, these data are summarized in the following two tables. Table A4-1 summarizes engineering and ROW characteristics; and Table A4-2 lists principal environmental characteristics for each of the route segments.

[1] The routing and environmental investigations usedto compare the options were conducted primarily in 2006 and involved the same types of analyses for both alternative routes. (Subsequently, more extensive field investigations and research was performed for Option A, after its designation as the preferred route

Table A4-1: Summary of Engineering and Right-of-Way Characteristics for Option A Transmission Line Segments

Segment Description	Length (Miles)	Existing ROW Width (Typical, Feet)	Existing Transmission Lines	Additional ROW (Easement) Required for New 345-kV Line (Y/N)	Additional Vegetation Clearing Required (Width and Approx. Acres)	Comments
Card Street Substation to Lake Road Substation (CT)	29.3	150 – 360 feet	345 kV 115 kV 69 kV	Y (1.5 miles)	150 feet (27 acres)	Additional easement needed to expand existing 150-foot-wide ROW through Mansfield Hollow State Park and Wildlife Management Area.
Lake Road Substation (CT) to Sherman Road (RI)	16.2	300-500 feet	345 kV 115kV	N	200 feet (85 to 95 feet in RI) (337.33 acres) (90 acres in RI)	
Sherman Road Substation to West Farnum Substation (RI)	9.0	300-700 feet	345 kV 115 kV	N	75-115 feet (100 acres)	
West Farnum Substation to Woonsocket Substation (RI)	1.3	250 feet	345 kV	N	100 feet (5 acres)	
Woonsocket Substation (RI) to Millbury Switching Station (MA)	19.6	125-270 feet	345 kV 115 kV	N	0-115 feet (50 acres)	

Table A4-2: Summary of Environmental Characteristics for Option A Transmission Line Segments

Segment Description	Length (Miles)	National Weltand Inventory Wetlands Traversed (Approx. acres within ROW)	Vegetation Clearing within Existing Maintained ROW and Expanded ROW (Acres)	Waterbody Crossings (Number)	State or Federally Designated Species of Concern Habitat (approx. Acres within 500 Feet of the ROW Centerline)	Designated Public Lands Within ROW (Acres)	Residences Located within 500 Feet of ROW Centerline (Approx. Number)
Card Street Substation to Lake Road Substation (CT)	29.3	98.6	554.8	59	27.8	65.3	107
Lake Road Substation (CT) to Sherman Road Substation (RI)	16.2	40.0	337.3	27	54.4	80.7	72
Sherman Road Substation to West Farnum Substation (RI)	9.0	13.2	122.6	28	6.3	51.6	66
West Farnum Substation to Woonsocket Substation (RI)	1.3	33.7	3.6	5	2.9	6.3	3
Woonsocket Substation (RI) to Millbury Switching Station (MA)	19.6	56.3	115.1	32	57.3	40.2	209
TOTAL	75.4	241.8	1,133.4	210	148.7	244.1	457

Notes: Vegetation clearing refers to all vegetation, within the existing maintained and expanded ROWs that would be required for the development of Option A along each segment.

2.0 Option C-2

The following text and tables summarize the facilities and route characteristics of Option C-2.

2.1 OPTION C-2 FACILITIES

Option C-2 would entail the construction of a new 74.4-mile, 345-kV line from CL&P's Manchester Substation in the Town of Manchester north to WMECO's Ludlow Substation in the Town of Ludlow (Hampden County, Massachusetts), and then east to National Grid's Carpenter Hill Substation in the Town of Charlton and Millbury Switching Station in the Town of Millbury (both in Worcester County, Massachusetts). This option also would require the construction of a second (new) 9.1-mile 345-kV line between National Grid's Sherman Road Substation in Burrillville, Rhode Island and its West Farnum Substation in North Smithfield, Rhode Island, as well as the reconductoring of 6.6 miles of the Little Rest to Palmer 115-kV circuit # W-175 in Massachusetts.

Overall, Option C-2 would require the development of 83.4 miles of new 345-kV transmission line, aligned generally along existing CL&P, WMECO, and National Grid ROWs that are presently occupied by 115-kV and 345-kV circuits. Option C-2 would involve the construction of 20.0 miles of new 345-kV in Connecticut; 54.4 miles in Massachusetts, and 9 miles in Rhode Island. Option C-2 would require removal of approximately 1,162 acres of vegetation from existing transmission ROWs for construction of new 345-kV facilities.

2.2 OPTION C-2 ROUTE CHARACTERISTICS

Option C-2 would pass through portions of the following communities in each state:

- *Connecticut*: Manchester, South Windsor, East Windsor, Ellington, and Somers.
- *Massachusetts*: East Longmeadow, Hampden, Wilbraham, Ludlow, Belchertown, Palmer, Brimfield, Warren, Brookfield, Sturbridge, Charlton, Oxford, Sutton, and Millbury.
- *Rhode Island*: Burrillville and North Smithfield.

The predominant characteristics of the Option C-2 route in each state are summarized below.

Connecticut

ROW Configuration

From Manchester Substation to Meekville Junction, the new 345-kV line for Option C-2 would be aligned within CL&P's existing 350 to 380-foot-wide ROW. This ROW is presently occupied by a 345-

kV and a 115-kV circuit sharing a line of steel-lattice towers, as well as two other 115-kV circuits sharing a parallel line of steel-lattice towers. As noted in Table A4-3, as part of the GSRP (Connecticut portion), CL&P proposes to separate the 345- and 115-kV circuit, leaving the 345-kV circuit on the existing line of structures and constructing an adjacent 115-kV circuit on a new line of steel monopoles. If this circuit separation is approved as part of the GSRP, the development of the additional 345-kV line as part of Option C-2 along the Manchester Substation – Meekville Junction segment could possibly require the acquisition of additional ROW (easement) from private property owners, causing additional environmental effects. For the purposes of this analysis, however, it is assumed that the Option C-2 route would be within the existing CL&P ROW.

Between Meekville Junction and the Connecticut/Massachusetts border, the Option C-2 route would be aligned within CL&P's existing ROW, which varies in width from 250 to 300 feet. This ROW is occupied by the existing 345-kV line on wood-pole H-frames or steel lattice towers. In addition, existing 115-kV lines are located along portions of the ROW in the towns of South Windsor and Somers. In South Windsor, the existing 115-kV double-circuit line would be removed and rebuilt in the ROW. The Option C-2 route would involve the addition of a new 345-kV line, constructed on various types of structures (e.g., H-frames or steel monopoles), within this ROW.

Environmental Features

The Connecticut portion of Option C-2 ROW would extend approximately 20.0 miles through a variety of land uses, ranging from industrial areas and densely developed residential subdivisions in Hartford County to wooded floodplains and agricultural lands in Tolland County. For example, between Manchester Substation and Meekville Junction, the ROW extends through a mixture of wooded areas bordered by residential development, the wooded floodplain of the Hockanum River, Interstate 84, and industrial/commercial areas. For approximately 4.7 miles from Meekville Junction through South Windsor (almost to the East Windsor border), the Option C-2 route would follow an existing overhead line ROW adjacent to residential subdivisions. In this area, an estimated 240 homes are located within 500 feet of either side of the centerline of the existing ROW.

In the Town of Somers, the Option C-2 route would follow the existing ROW linearly along the wooded floodplain of the Scantic River and its tributaries for approximately 2 miles. In addition to the Scantic River, other primary watercourses crossed by the Connecticut portion of Option C-2 include the Hockanum River in Manchester, Podunk River in South Windsor; Pecks Brook, Bradley Brook, Creamery Brook, and Ketch Brook in Ellington; and Abbey Brook, Gulf Stream Brook, and Hall Hill

Brook, Thrasher Brook, and Watchaug Brook in Somers. The route also passes by the eastern portion of Vinton's Mill Pond in South Windsor.

Option C-2 would traverse Interstate 84 and U.S. Route 6 (in Manchester), as well as State Routes 30 and 194 (in South Windsor), 140 (Ellington), and 190 and 83 (in Somers). In South Windsor, the Option C-2 ROW would cross the eastern boundary of Nevers Road Community Center Park. In Somers, the Avery Middle School, Somers High School, and an elementary school are all located off 9th District Road, approximately 0.4 mile east of the Option C-2 route.

Massachusetts

Option C-2 would traverse approximately 54.4 miles along existing ROWs in Massachusetts. These ROWs include the following segments:

- From the Massachusetts/Connecticut border north to Hampden Junction and then continuing north to WMECO's Ludlow Substation in the Town of Ludlow;
- East from the Ludlow Substation to National Grid's Carpenter Hill Substation, located in the Town of Charlton; and
- East from the Carpenter Hill Substation to National Grid's Millbury Switching Station, located in the Town of Millbury.

The ROW configurations and predominant environmental features along each of these segments are discussed as follows.

Connecticut Border to Ludlow Substation

ROW Configuration

Between the Connecticut border and Ludlow Substation, the Option C-2 route would be aligned generally within an existing 250-foot-wide WMECO ROW. WMECO's 345-kV line on, wood-pole H-frames occupies this corridor alongside a steel-monopole line which supports one 115-kV circuit north of Hampden Junction and two 115-kV circuits south of Hampden Junction.

Environmental Features

Entering Massachusetts from Connecticut in the Town of Hampden (Hampden County), the Option C-2 route would continue to be aligned generally along the floodplain of the Scantic River. In this area, the floodplain is bordered by residential development to the west and a mix of agricultural land, forested areas, and wetlands to the east. Between Hampden Junction and the Ludlow Substation, Option C-2 would traverse the Towns of Hampden, Wilbraham, and Ludlow.

The principal environmental features along the ROW include crossings of Watchaug Brook and a heron rookery (in Hampden); the South Branch of the Mill River and the North Branch of the Mill River, as well as white cedar swamps in Wilbraham; the Chicopee River, which forms the border between Wilbraham and Ludlow; and Higher Brook and Fuller Brook in Ludlow. The primary highways traversed include U.S. Route 20 and the MassPike (Interstate 90). Although the Option C-2 route would be aligned within an existing utility easement between the Connecticut border and the Ludlow Substation, an additional 75 to 100 feet of this ROW would have to be cleared of vegetation to accommodate the new 345-kV line.

Further, as noted in Table A4-3, as part of the GSRP (Massachusetts portion), WMECO has identified the Hampden Junction to Ludlow Substation segment as part of the “noticed-alternative Southern Route” for the development of the new 345-kV line that is required to complete a 345-kV transmission loop to better serve the Greater Springfield region. Although the “noticed-alternative Southern Route” is not WMECO’s preferred alignment for this new 345-kV transmission line, it is possible that the Massachusetts Energy Facilities Siting Board could determine that the GSRP be developed along this route. If so, both the GSRP 345-kV line and the Interstate Option C-2 345-kV line would have to be developed between Hampden Junction and Ludlow Substation and, consequently, substantial additional lands likely would be affected. For example, since each of the proposed 345-kV transmission lines would require 100 to 150 feet of ROW, depending on the structure type, and there is only approximately 140 feet of ROW width available, a minimum of 45 feet of additional ROW width would be required. New easements from private property owners would be required to accommodate this ROW expansion. In addition, double the amount of vegetation clearing would be required (amounting to close to 200 acres) to accommodate the two new 345-kV lines. Lastly, the collocation of three 345-kV lines on one ROW, although permitted by reliability criteria, would make the system more vulnerable to an extreme contingency than would be the case if the Option A were chosen. For the purposes of this analysis for Option C-2, it is assumed that the “noticed-alternative Southern Route” is not selected for the GSRP.

Ludlow Substation to Carpenter Hill Substation

ROW Configuration

From the Ludlow Substation east to Carpenter Hill Substation, Option C-2 would traverse approximately 26.7 miles within an existing 250 to 335-foot-wide transmission line ROW through eastern Ludlow (Hampden County), and then would continue east through the southernmost portion of the Town of Belchertown in Hampshire County, before traversing back into the Hampden County and extending east through the towns of Palmer and Brimfield. The route would continue east into the Worcester County towns of Warren, Brookfield, Sturbridge, and Charlton.

The existing ROW along which the Option C-2 345-kV line would be installed is presently occupied by another 345-kV line on wood-pole H-frame structures, as well as 115-kV lines on wood-pole structures. The proposed Option C-2 345-kV line would be constructed on wood- or steel-pole H-frames. As part of the Option C-2 development, portions of the existing 301 Line in the towns of Palmer and Belchertown would be removed and reconstructed within the same ROW.

Environmental Features

Along this segment of the Option C-2 route, principal environmental resources include Broad Brook (near the Red Bridge Pool [Chicopee River Reservoir]) in Ludlow; the Swift River (which forms the border between Belchertown and Palmer; the Ware River in Palmer; the Quaboag River (which serves as the border between Palmer and Brimfield); Penny Brook and Taylor Brook in Brimfield; Sessions Brook in Warren; Trout Brook in Brookfield; McKinstry Brook in Sturbridge; and Cady Brook in Charlton. In Sturbridge, Option C-2 would follow the existing transmission line ROW across Wells State Park, a popular destination for camping and hiking. The 1,400-acre park includes various trails, including those leading to scenic vistas of Carpenter Rocks, which the transmission line ROW traverses. The transmission line ROW traverses northwest-to-southeast through the park, north of Walker Pond.

This segment of Option C-2 also traverses the I-90 (Massachusetts Turnpike) three times, as well as U.S. Route 20. It also crosses Commonwealth Routes 181, 32, 67, 19, 148, 49, and 169.

Carpenter Hill Substation to Millbury Substation

ROW Configuration

Between these two substations, Option C-2 would traverse approximately 16 miles through portions of the towns of Charlton, Oxford, Sutton, and Millbury in Worcester County. The route would follow an existing ROW that is approximately 250 to 335 feet wide and that is presently occupied by an existing 345-kV line on wood-pole H-frames, as well as (in certain locations) 115- and 69-kV lines on wood-pole structures.

Environmental Features

The principal watercourses traversed include the Little River in Charlton; the French River (and an associated cedar swamp) and Wellington Brook in Oxford; and the Blackstone River in Millbury. The Blackstone River as well as surrounding portions of the Town of Millbury are within the John H. Chafee

Blackstone River Valley National Heritage Corridor, which was established by Congress in 1986 to recognize the national significance of the region surrounding the river between Providence and Worcester as the "birthplace of the American Industrial Revolution". The heritage corridor is an affiliated area of the National Park Service. Within this corridor, the Blackstone River Bikeway, which will link Worcester to Providence, extends along the river. The Millbury Switching Station is located approximately 0.1 mile east of the Blackstone River.

This segment of the Option C-2 route also would traverse the Merrill Pond Wildlife Management Area in Oxford and Sutton, and near Ramshorn Pond and Singletary Pond in Sutton. The route crosses or is located near the following principal transportation areas: Interstate 395, Massachusetts Routes 12, 146, and 122A, and the Oxford Airport.

Rhode Island

ROW Configuration

The Rhode Island component of Option C-2 would extend for approximately 9 miles between the Sherman Road and West Farnum Substations, traversing portions of the towns of Burrillville and North Smithfield in Providence County. In this area, the new 345-kV transmission line would be located within an existing 300- to 700-foot-wide ROW which is presently occupied by a 345-kV line on wood-pole H-frames and a 115-kV line (on wood poles). An additional 75- to 115-foot-wide portion of this ROW, which is presently not maintained, would have to be cleared of vegetation for the development of the new line.

Environmental Features

For the most part, the 9-mile ROW segment extends through sparsely developed, forested areas. In Burrillville, the route would traverse approximately 0.8 mile across the Black Hut State Wildlife Management Area (which is managed by the Rhode Island Department of Environmental Management, Division of Fish and Wildlife), as well as Tucker Brook (a tributary of the Branch River). In North Smithfield, the route would traverse the Slatersville Reservoir, as well as portions of a cedar swamp near the West Farnum Substation. The Sherman Road-to-West Farnum Substation segment also would involve crossings of State Routes 7, 102 and 5, as well as local roads.

3.2.1 Option C-2 Data Summary Tables

Right-of-way, environmental, and engineering data were compiled for each segment of Option C-2 based on the review and analysis of available Geographic Information System databases, maps, and aerial photographs. This data is summarized in the following two tables. Table A4-3 summarizes engineering and ROW characteristics; and Table A4-4 lists principal environmental characteristics for each of the route segments.

Table A4-3: Summary of Engineering and Right-of-Way Characteristics for Option C-2 Transmission Line Segments

Segment Description	Length (Miles)	Existing ROW Width (Typical, Feet)	Existing Transmission Lines	Additional ROW (Easement) Required for New 345-kV Line (Y/N)	Additional Vegetation Clearing Required (Width and Approx. Acres)	Comments
Manchester Substation to Meekville Junction (CT)	2.5	350 – 380 feet	345-kV 115-kV	N	85 feet (22 acres)	Additional land disturbance would be required if the 115-kV and 345-kV line separations proposed for GSRP Connecticut are approved. See Note (a).
Meekville Junction (CT) to Hampden Junction (MA)	18.1	250-300 feet	345-kV 115-kV	N	60-85 feet (96 acres)	
Hampden Junction to Ludlow Substation (MA)	11.0	250 feet	345-kV 115-kV	N	60 feet (80 acres)	Additional ROW acquisition and clearing would be required, depending on the final route of the GSRP Massachusetts 345-kV line. See Note (b).
Ludlow Substation to Carpenter Hill Substation (MA)	25.9	250 – 335 feet	345-kV 115-kV	N	75 – 80 feet (275 acres)	Additional land disturbance may be required for temporary 345-kV relocation to prevent outages. See Note (c).
Carpenter Hill Substation to Millbury Switching Station (MA)	16.0	250 – 335 feet	345-kV 115-kV 69-kV	N	75-80 feet (150 acres)	
Sherman Road Substation to West Farnam Substation (RI)	9.1	300-700 feet	345-kV 115-kV	N	75-115 feet (100 acres)	

Notes:

(a) As part of the Greater Springfield Reliability Project (GSRP), Connecticut portion, CL&P proposes to separate the 115-kV and 345-kV circuits that presently share the same structures along the ROW between the Manchester Substation and Meekville Junction. The implementation of both the GSRP (Connecticut) 115-kV/345-kV circuit separation and a new 345-kV line for Option C-2 would require additional vegetation clearing, and possibly additional ROW width.

(b) As part of the GSRP (Massachusetts portion), WMECO has identified the Hampden Junction to Ludlow Substation segment as part of the "noticed-alternative Southern Route" for the development of a proposed new 345-kV circuit to complete a 345-kV transmission loop to better serve the Greater Springfield region. Although the "noticed-alternative Southern Route" is not WMECO's preferred alignment for this new 345-kV transmission line, it is possible that the Massachusetts Energy Facilities Siting Board could nonetheless select this alternative for the GSRP. In that case, both the GSRP 345-kV line and the Option C-2 345-kV line would have to be developed between Hampden Junction and Ludlow Substation and substantial additional ROW would be affected (e.g., potential requirements for the acquisition of additional easements from private landowners; increased vegetation clearing to accommodate a much wider ROW). *This analysis for Option C-2 assumes that the "noticed-alternative Southern Route" is not selected for the GSRP*.

(c) In the towns of Palmer and Belchertown, approximately 3 miles of an existing 345-kV line would have to be relocated to install the new 345-kV line. This could require the development of a temporary transmission line to minimize the outage required for the existing line. No specific location for such a temporary line has been identified; however, such a line would involve additional land disturbance that is not defined in this table.

Table A4-4: Summary of Environmental Characteristics for Option C-2 Transmission Line Segments

Segment Description	Length (Miles)	NWI Wetlands Traversed (Approx. acres within ROW)	Vegetation Clearing within Existing Maintained ROW and Expanded ROW (Acres)	Waterbody Crossings (Number)	State or Federally Designated Species of Concern Habitat (approx. Acres within 500 Feet of the ROW Centerline)	Designated Public Lands Within ROW (Acres)	Residences Located within 500 Feet of ROW Centerline (Approx. Number)
Manchester Substation to Meekville Junction (CT)	2.5	52.7	68	6	0	0	10
Meekville Junction (CT) to Hampden Junction (MA)	18.1	141.5	320	61	85.6	24.7	167
Hampden Junction to Ludlow Substation (MA)	11.0	111.9	158	12	232.2	51.1	213
Ludlow Substation to Carpenter Hill Substation (MA)	25.9	34.0	280	43	68.6	153.5	131
Carpenter Hill Substation to Millbury Switching Station (MA)	16.0	31.9	214	28	91.7	49.5	97
Sherman Road Substation to West Farnum Substation (RI)	9.1	13.2	123	28	6.3	51.4	66
TOTAL	**82.6**	**385.1**	**1,163**	**178**	**484.4**	**330.2**	**684**

Notes:

Vegetation clearing refers to all vegetation, within the existing maintained and expanded ROWs that would be required for the development of Option C-2 along each segment.

3.0 Comparison of Option A and C-2 Routing/Environmental Features

Option C-2 would require the construction of 83.4 miles of new 345-kV line, or 7 (9%) more miles than the development of the new 345-kV line along the 75.4-mile Option A. In addition, compared to Option Av, Option C-2 would involve:

- Greater impacts to wetlands, as designated on National Wetland Inventory (NWI) maps. Based on an analysis of the mapped NWI wetlands in relation to the two route alternatives, Option C-2 would traverse an estimated 385 acres of wetlands, compared to approximately 242 acres along Option A.
- Alignments through or near more areas of known habitat for state or federally-listed protected species (i.e., threatened, endangered, or special concern species). Option C-2 would traverse or be located within 500 feet of approximately 484 acres of such mapped habitat, compared to 149 acres along Option A.
- Alignment through more park or other designated public lands, such as wildlife management areas. Option C-2 would cross approximately 330 acres of such public lands, including Wells State Park in Sturbridge. In comparison, Option A would traverse approximately 244 acres of public lands, including Mansfield Hollow State Park and Mansfield Hollow Wildlife Management Area.
- Alignments in proximity to 47% more residences than along Option A. Portions of Option C-2 would traverse through more densely populated areas, resulting in an estimated 684 homes within 500 feet of the route centerline. In comparison, Option A would be aligned within 500 feet of 460 homes.

Both options would be developed within existing transmission line easements, but Option A would potentially require additional easement (i.e., ROW expansion) through portions of Mansfield Hollow State Park and the Mansfield Wildlife Management Area in the Connecticut towns of Mansfield and Chaplin. As proposed, Option C-2 would not involve any additional ROW acquisition. However, if the Greater Springfield Reliability Project is developed as proposed between Manchester Substation and Meekville Junction, and/or if the GSRP “noticed alternative Southern Route” is selected for the project between Hampden Junction and Ludlow Substation, substantial additional ROW would have to be acquired to accommodate the Interstate 345-kV line along these segments of Option C-2. Further, the supplemental expansions of these ROW segments would result in potentially significant additional environmental effects if the existing utility corridors must be widened into previously undeveloped upland and wetland forested areas.