Long-Term Planning Considerations Based on a "Technical Balance Sheet" for Introducing High Voltage Cables as Opposed to Overhead Lines in Distribution and Transmission Networks

Frank Anthony Auditoré

LineTech Consulting, Hamilton, New Zealand

ABSTRACT — **The paper objectively reviews long-term planning considerations based on the concept of a "technical balance sheet" for introducing high voltage cables in distribution and transmission networks. System planning and operation has the objective of developing a transmission network of sufficient capacity with high availability and reliability at minimum cost. The installation of partial or complete underground cabling is a result of significant system planning and operational implications. Traditionally, technical limitations and cost factors of cable installations have been major considerations for installing cables. Additional considerations are: application and planning considerations; environmental constraints, comparative investments, and perspectives.**

Index Terms — **Technical balance sheet, underground cabling, overhead lines, planning, financial evaluation, gas insulated lines, high temperature superconducting cables.**

I. INTRODUCTION

The evaluation and recording of current business practices are represented in an organisation's "financial accounts". In particular, the balance sheet is of relevance. These are purely financial evaluations that are void of any *direct* technical sustainable measures. Although providing an essential indication of the financial sustainability of an organisation, this financial evaluation neglects the sustainability of the technical assets. Asset life expectancy is based on the depreciation period. It is a fact that operating plant either meet, exceed or fail prematurely before this depreciation period. The true period of asset life expectancy is dependant on the design, operating environment and the utilization of the asset. Each of the former influences the life expectancy of each other.

This paper is based on the author's hypothesis of a "technical balance sheet". This hypothesis transforms the traditional financial balance sheet into a technical balance sheet.

Influencing the former decision making, modern day demands on international electricity utilities require that operational plant exceed their initial life expectancy. The concept of life expectancy and the definition thereof by various decision makers is discussed in the paper. The main decision makers include design engineers, capital investors and asset owners. Often, each of the former has different time periods for life expectancy. Furthermore, life cycle costs are also viewed differently by each. Regarding upgrading of networks; an important consideration when compared to overhead lines is that cables do limit engineering choices. The paper discusses some distinct advantages overhead lines have from a future upgrade point of view. Depending on the initial design, overhead lines can be successfully upgraded to higher energy transfer capabilities.

II. BACKGROUND

A financial statement summarises a company's assets, liabilities and shareholders' equity within a specified time period. It provides investors an overview as to what the company owns and owes, as well as the amount invested by the shareholders or owners. It is comprised of the following formula:

Owner's Equity = Assets - Liabilities

The sum of each of the three entities of the balance sheet aggregate different accounts within it. Accounts such as cash, inventory and property are on the asset side of the balance sheet, while on the liability side there are accounts such as accounts payable or long-term debt. Specific accounts on a balance sheet will differ by company and by industry.

The author's objective is to develop a non-financial balance sheet model that represents the non-financial sustainability of an organisation. The concept of "*non-financial*" is holistic and includes non-technical issues such as human resources, goodwill, information security, etc.

This paper focuses on the *technical* issues of a "*non-financial*" balance sheet, and more specifically on the production assets: cables and overhead lines.

III. TECHNICAL BALANCE SHEET MODEL

The proposed technical balance sheet model basically determines the orgainsation's equity in term of overall technical value by identifying the remaining life of its assets, and managing the expected risks. This is represented in a simplified model as follows:

$$OE \approx L_e - R_e \qquad (eq.\ 1)$$

$$OE = L_e - k.L_e \qquad (eq.2)$$

$$OE = L_e(1 - k) \qquad (eq.\ 3)$$

Where: OE is the organisation's equity, L_e: the remaining life expectancy based on the power cable and overhead line utilization, design load levels and operating limits; and R_e: are risks related to accelerated aging risks attributed to operating, environment, utilisation, maintenance practices, skills shortage, technical obsolescence, availability of spares and emergency planning. K is the risk factor for either derating or extending L_e. The unit of measure for the above technical balance sheet is not financial currency as in the case for a financial balance sheet, but rather in *years*. The advantage of using years as a unit of measurement is that it is an international and common based unit. It also addresses the economic disparity between currencies when performing international comparative studies.

IV. ORGANISATION EQUITY

The organisation's equity (or worth) in terms of technical issues is considered to be the net life expectancy of the production assets. The net life is the expected life at hand less the forecasted risks. The expected benefit from providing such a performance measure is that an organisation can evaluate its technical sustainability for the foreseeable future. This is different to a financial balance sheet that presents monetary components in a specific time period – annually.

However, the evaluation of a technical balance sheet is dynamic and obviously changes within a specified time period. The evaluation of expected risks may be extremely resource intensive therefore justifying the period of evaluation to be longer than a year. Bi-annual evaluation may be a consideration.

V. DETERMINING REMAINING LIFE-EXPECTANCY

Determining the remaining life expectancy of electricity utility plant and equipment is extremely topical and is included in most asset management research agendas. Cigré is such an organisation carrying out extensive study.

Traditionally the loss-of-life is computed based on analyzing the loading profiles, identifying the appropriateness of refurbishment or replacement. Instances where overloading have exceeded design limits are to be used to derate the remaining life expectancy. The evaluation of utilization will initially identify the utilization criteria (voltage, ampacity, number of operations, maintenance practices, etc.). Thereafter, appropriate design load levels and operating limits will be determined; followed by an audit. A comparison between the expected performance and actual performance will result into a performance gap analysis.

The appropriateness of refurbishment must also be considered on the expected remaining life of overhead lines should such refurbishment take place. Weighed against the cost of replacement it may be more feasible to replace an existing item of the overhead line and deploy it in a less demanding operating environment – glass disc insulators replaced with non-ceramic insulators.

Additional aging information can be provided by considering product manufacturing techniques (e.g. steam cured versus dry cured XLPE cable insulation) and related cable failures. Similarly, for overhead lines the failure rate of non-ceramic insulators in respect to the different product developments can be considered. EPRI have built up an extensive data base on the subject of non-ceramic insulator failures.

With appropriate maintenance being applied, overhead lines have a longer life expectancy than underground cables. Service experience of high voltage lines across Europe has shown that pylons/towers have a service life of 50-60 years and refurbishment of conductors and fittings is required at approximately 30-year intervals. In general, transmission cables have an estimated service life of 40 years, but service experience in the UK is that some oil-filled cables are ageing prematurely and need to be replaced at significant cost. Other European electricity utilities have also suffered maintenance problems with cable systems, but principally with the joints and the terminal equipment linking the cable and the overhead line [1].

VI. DETERMINING RISKS

6.1 Introduction

Risks are associated, but not limited to the following: operating environment (E_o), plant utilization (U_p), frequency of refurbishment (R_f), upgrading opportunities (R_u), applied design standards (S_d), and applied maintenance standards (S_m). Therefore, R_e from *eq. 1* can be represented as:

$R_e \approx E_o + U_p + R_f + R_u + S_d + S_m \ldots$

$R_e = k_1.E_o + k_2.U_p + k_3.R_f + k_4.R_u + k_5.S_d + \ldots$ (*eq. 4)*

K_1, k_2, k_3, k_4, k_5, k_6, … are the risk factors for each of the above components. The challenge is to quantify the magnitudes of both the risk factor and the risk component. As a base, it is proposed that the initial financial depreciated period be assumed. This is appropriate reasoning as it coincides with a financial base for cross reference. For an expected remaining life expectancy of 30 years and a depreciation period of 30 years, the risk factor will be zero. If for the same depreciation period (30 years) the expected life is 60 years, the risk factor is -1. The negative value has the effect of increasing the organisation equity (OE) in equations 2 and 3.

If the remaining life expectancy is less than the depreciated period; the effect is a positive value risk factor with reduced organisation equity (OE). This is illustrated in *Figure 1: Risk Factor for Determining Risks.*

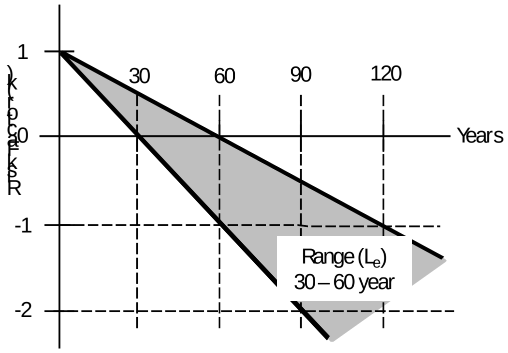

Figure 1: Risk Factor for Determining Risks.

Additional risks to be considered are skills shortage, technical obsolescence, availability of spares, emergency planning, and increase in demand exceeds supplier capacity.

6.2 Statistical process

The quantification of *eq.* 4 requires further research. This may be forthcoming from asset management study committees within Cigré. Stemming from personal observations the author suggests applying multivariate analysis, such as factor analysis, as the final appropriate research analytical tool. More specifically, the findings of

J. Stevens [2] suggest that exploratory factor analysis is relevant. Validation studies could be reviewed with the construct validation study being the proposed method. However, although the construct validation process of Kivlighan and Wampold [3] deemed appropriate, a modification to the process could be introduced from the suggestions of Johnson and Wichern (p517) [2].

The complexity of analysing the relations among a set of random research variables observed includes the accountability for determining inter-correlations and postulating a set common factor. Gorsuch (1983) reminded researchers that they "are united in a common goal in that they seek to summarise data so that the empirical relationship can be grasped by the human mind." (p2) [3]. One statistical means of achieving the former is by applying the process of factor analysis. The purpose of factor analysis "is to summarize the interrelationships among the variables in a concise but accurate manner as to aid in conceptualization." (p2) [3].

Having identified factor analysis as the research analytical tool, it would be theoretically appropriate to determine what type of factor analysis is most relevant to this study. The options are either *exploratory* factor analysis (EFA) or *confirmatory* factor analysis (CFA).

As this hypothesis is based on more of a *theory-generating*, rather than a *theory-testing* procedure, it is considered justified in assuming the exploratory factor analysis is the applicable approach. This assumption can be further substantiated by the lack, or more accurately the scarcity, of a strong empirical base. It must, however be acknowledged that the data obtained in this research is based on sound engineering performance measuring aides which have been the topic of discussion at international forums such as IEEE, IEE and Cigré.

6.3 Operating Risks

Accurately measuring electric grid reliability is difficult. Most measures of electric reliability focus on two measurables [1]:

- The frequency with which a customer sustains a power outage, i.e., the number of power outages per year, or the number of outages per year for a mile of distribution circuit.
- The duration of power outages, i.e., the number of minutes per year a customer is without power.

Comparing the reliability of overhead power lines to underground power lines is difficult. Many utility outage-reporting systems do not separately track overhead and underground systems. Furthermore, most underground circuits have at least a component above the ground. Installing monitoring equipment to identify and diagnose outages on the overhead and underground components of the same circuit can be expensive.

Cables have at present a good record of reliability with records showing that an average cable faults show 0,072 failures/100 circuit km/year, with overhead lines showing around 0,170 failures per 100 circuit km/year. These average figures are confirmed by a study carried out by the DISCAB Group over the last 12 years as presented in the ICF Congress in Barcelona in 1995.

With recent developments of new technologies, cable systems show a decreasing trend of annual rates of failure. On the hand, overhead lines maintain a relatively constant failure rate. This is mainly due to climatic reasons such as wind, ice, snow and fog. However, the time required for locating and repairing a fault is greater in cables than in overhead lines. The time of outage of a cable owing to a fault may be 25 times more than the time required for an overhead line of the same length.

Furthermore, transient faults affect overhead lines at an average rate of 2,3 times per 100km/year. Most transient faults are cleared through reclosure devices without any loss of supply. Such a form of outage is not present in cable systems.

The load of an overhead line and its capability to carry overloads is affected by the ambient air temperature and wind speed. Due to the unpredictability of both these parameters, the calculated continuous loading is set at average parameters. This can in some cases be about 40% of the total actual capacity. During overloads the temperature of the conductor can reach the design limits within minutes.

In comparison, soil temperature is relatively constant, with an estimated variation range within ± 5ºC throughout the whole year. Therefore, the calculated continuous current permitted for underground cables can more closely match its capacity. In regard to overloads, again the stable environment and the bigger thermal capacity means that overloads of 20% can be accepted for up to 48 hours without exceeding the design limits of cables.

Regarding the reliability aspects of supply, or (n-1) redundancy, realized in the cable route, is often demanded by the utility. This means a twin system for the overhead line. Redundancy in cable is possible with a three-phase single-core cable system with core-redundancy. This is illustrated in *Figure 2: Four-core cable system.*

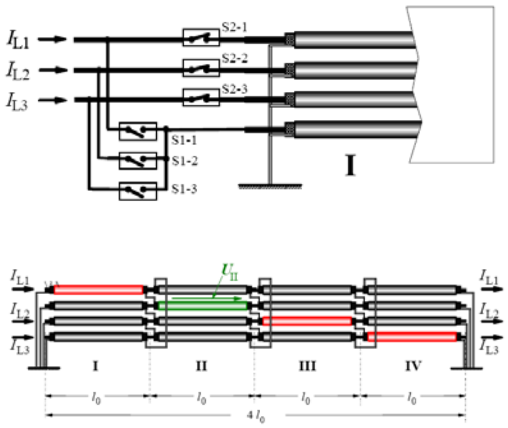

Figure 2: Four-core cable system.

When undergrounding cables, often two parallel systems are laid into the trench side by side. For the transmission of great power, the single core cables will not be arranged bundled but in a flat formation. In order to suppress sheath- or screen-losses by circulating currents, a cross-bonding of the sheaths/screens is carried out [4].

However, a requirement to implement the former is an arrangement of the four cores in a way, that, dependent on the operating situation, the three current-carrying cores are arranged approximately symmetrically. This leads to an induction of longitudinal screen voltages of similar values.

The ability to apply this design option and manage the transmission network is a big advantage for cable systems. Furthermore, temperature monitoring is today a technology readily available for underground systems. This safely optimises the utilisation of the network at any point in time.

Existing grids are mainly built with overhead lines. The placing of underground cables can sometimes cause network problems. Indeed, due to the characteristics of an underground cable load-flow and short-circuit problems may arise. Upgrading of an existing overhead line is possible and virtually impossible with an underground cable. Given the problems to build new lines or to place new cables this is an additional advantage in favour of overhead lines. A review of the comparative reliability data that are available indicates that the frequency of outages on underground systems can be substantially less than for overhead systems. However, when the duration of outages is compared, underground systems lose much of their advantage [5].

6.4 Environmental Risks

Due to the necessary space for repairing and maintaining the underground cable, the land must remain free of construction or lengthy rooted trees planted above and along the cable throughout its lifetime. This contributes to a large use of land similar to the width of a secondary road (from 13 to 14 metres for a 400 kV underground cable with two circuits and 2 cables per phase) [6].

Decommissioning of overhead lines is easier than for cables. In the case overhead lines, they need to be dismantled and nearly all the components can be recycled. Cables have to be removed from trenches and tunnels and the insulation materials (which may include oil or gas) have to be removed prior to any recycling.

The land that needs to be kept free for overhead line is limited to the towers, which are generally spaced at least every 350 m and to the access roads built for their construction and removed after completion.

Over the past three decades, a significant amount of research has been carried out worldwide into examining whether electricity and in particular, the presence of electric and magnetic fields

(EMFs) have an adverse impact on health. EMFs are produced both naturally (e.g. thunderstorms) but also by the production and transmission of electricity [1].

Electric fields can be screened by structures such as buildings, trees and fences but magnetic fields pass readily through most structures.

A large electricity pylon carrying a 380/400kV conductor produces around 5 - 10μT directly under the line and between 3,000 – 5,000 volts per metre. Underground cables can produce higher magnetic fields directly above them than an overhead line as the physical distance from the underground cable and the ground is smaller. For example, 400kV cables can produce over 30μT at ground level falling to 10μT at 2 metres above the ground. The field falls rapidly with distance to the side and the way the cable is constructed (with insulation material and concrete covers), they produce no electric field.

Two major benefits of underground cables are that they are not susceptible to storm and icing damage. In addition, they are far less likely to cause death or injury due to accidental contact with the overhead lines.

6.5 Transmission losses [1]

Losses considered in electrical conductors are Joule (I^2R) losses and capacitive reactive power.

The I^2R losses are energy losses caused by the heating-up of an electrical conductor through which an electric current flows. Since the dissipation of heat produced by the current flow is less efficient than for overhead cables, the cross-section of conductors used in underground systems is the twice diameter of that used for overhead lines. Hence, the Joule losses in buried lines are 2-3 times lower than in overhead lines.

Capacitive reactive power is the current flow that reduces the power conveyed. In underground systems, this phenomenon is 20-40 times higher than in overhead systems. It increases with the line length and voltage rating. To reduce this current, reactive power compensation systems are set up every 20 km in 400 kV lines. These systems are similar to substations with a ground space requirement of about 5,000 m^2.

Furthermore, the percentage of losses from underground cable depends on the load. Compared with overhead lines cables have advantages at high loads but have disadvantages at low load situations. The situation may not be generalised and should be investigated case by case depending on the situation of the respective grid or section of the grid.

400 kV underground cable has other significant impacts regarding use of land and visual impacts: joint bays (at least every 500/900m), connections to the OVERHEAD LINE (about 2000m^2), reactive compensators every 20 to 30 km (for XPLE and oil-filled cables, additional land use of up to 5000 m^2).

Security issues affecting transmission losses may come into account in some areas. Once installed cable systems are less prone to either sabotage or theft of materials or energy.

6.6 Political/Regulatory considerations

In certain countries there are certain political or regulatory issues that relate specifically to the construction of aerial lines or underground cables. For example Belgium, has a voluntary ban on the construction of new overhead lines and in France, there are agreements between government and industry regarding policies and targets for undergrounding as opposed to overhead lines. In other European countries, the approval process can be difficult and long, as the government can refer major infrastructure projects to a Public Enquiry.

6.7 Components' recycling and environmental impact [1]

Decommissioning of overhead line is considered an easier task than for cables. The operation, which consists in returning the sites to their initial state following the dismantling of a link, is more complex and longer in the case of underground cable than in the case of an overhead line.

As regards the recycling of the components, it is observed that nearly all components from overhead line and underground cable can be recycled. The efforts to remove cables from trenches and tunnels and to separate the underground cable materials are more complicated than dismantling and recycling of overhead line materials. Possible different lifetimes of overhead line and underground cable shall be investigated prior to final comparison about recycling and environmental impact of the two technologies.

It should also be noted that the quantity of SF_6 used in the GIL insulating mixture is not ecologically friendly and contributes to the greenhouse effect.

The effect on the environment from cables is not always necessarily less than from OVERHEAD LINE. The better visual impact of cables especially at the HV and EHV level must be balanced against the increased use and movement of soil, restrictions of use of land above the cables, influences on the heat balance of the soil, considerably longer time for installation, reduced life time and new installation after 30-40 years.

Laying underground cables takes more time than constructing the equivalent length of overhead line because of the time required to dig open trenches, the time to manufacture joint bays and the season open for construction that is chosen to limit the damages on the environment (no site work during spring due to birds or rare species of flowers /plants)

Therefore, innovative methods for construction, laying and installation of underground cable systems have gained practical importance. On one hand, duration of public and environmental disturbances due to open trenches are more and more diminished by the introduction of trench-less construction methods such as directional drilling or tunnels. On the other hand, these particular laying techniques increase considerably the construction costs.

VII. Demographic Considerations

An interesting observation in the USA is the migration of population to coastal areas. This is illustrated in *Figure 3: Population growth in coastal areas between 1960 and 1990.* The migration between 1960 and 1990 was 38 million people [7].

Accompanied with this increase in population was an increase in the number of hurricanes. This is illustrated as the 5 year running mean in *Figure 4: Number of Atlantic Category 3-5 hurricanes between 1900 and 2005.*

This observation provides input into decision making for the development of electrification of coastal areas.

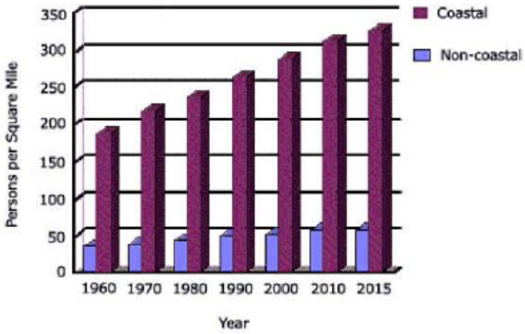

Figure 3: Population growth in coastal areas between 1960 and 1990.

The risk factor can be reduced with the installation of cable as opposed to overhead lines.

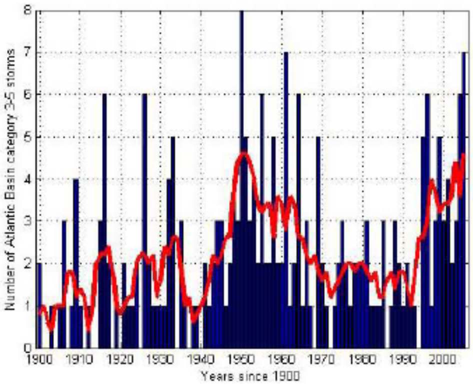

Figure 4: Number of Atlantic Category 3-5 hurricanes between 1900 and 2005.

VIII. Design Considerations

8.1 Fault current earth return

An important and often neglected difference in the design of overhead lines and cable networks is the distribution of fault current. In cables the cable sheath conducts the largest percentage of fault current. Typical values may be 80-90%. The remaining fault current relies on the earth return and this magnitude is dependent on the soil resistivity which is in parallel with the cable sheath. In comparison overhead lines without overhead shield wires rely solely on the earth return path. The fault current on overhead lines with connected shield wires split between the overhead shield wire and the earth return path.

Depending on the length of overhead, size of overhead shield wire and soil resistivity, the shield wire may conduct up to 20-30% of the fault current.

8.2 Cable developments

Recent development focuses primarily on smaller cable dimensions and weights with the objective of reducing product and installation costs. As a consequence longer shipping lengths, less joints, ease of installation and shorter erection times provide cost savings opportunities for both manufacturers and operators.

It is reasonable to state that after years of R&D, present technologies in XLPE cables have reached a plateau. Any additional benefits that may still be obtained will be in optimising laying techniques. It is estimated that this will serve to save no more than 10 to 15% on the costs of cables. Installation techniques include:

- Longer shipping lengths, fewer joints, ease of installation and reduction of erection times of cable systems.
- Mechanised laying methods that avoid extensive excavations and transport of material.
- ‘Trenchless’ methods of cable installation, such as thrust boring and directional drilling which reduce time installing cables around motorway and railway crossings and in rural areas where habitat needs to be preserved.
- Increased use of micro tunnels to lay longer cable lengths that save on joints, installation time and costs.

8.3 Gas Insulated Line (GIL) [8]

400 kV GIL offers a complementary solution to XLPE cables. Their initial objective was to reduce clearances in comparison to air-insulated overhead lines. The technology derives from transformer technology and comprises an aluminium tube of about 600 mm diameter filled up with insulating pressured gas SF_6/N_2. The conductor is positioned in the centre of tube and is separated from the metallic tube by regular spacers. Finally, an outer protection of anticorrosion coating is applied on the tube exterior.

The GIL alternative is viable when very high transmission capacity (2000 to 4000 MW) is to be transmitted over short distances.

An advantage of GIL is that their electric field is zero, while their magnetic field is very low. However, disadvantages may include:

- Large diameter of each phase (600mm), makes such a system rigid difficult to install in urban areas.
- GIL uses large quantities of SF_6 which is a potent greenhouse gas and contributes to global warming. With the danger of leakage the need for continuous monitoring of pressure is evident.
- The life expectancy of GIL is speculated to be between that of overhead lines and underground XLPE cables.

Figure 5: GIL tunnel.

Gas insulated lines using sulphur hexafluoride (SF_6) were first used in the 1970s typically within substations to connect switchgear with overhead lines.

More recently SF_6 has been replaced by a mixture of SF_6 and Nitrogen (N_2) which has a far greater insulating capability allowing the transmission of voltages up to 550kV and with longer system lengths (potentially more than 50 km).

GIL's have a high overload, high short circuit withstand capability and can be integrated easily into a network of overhead lines.
Great care is required to avoid any infiltration of dust or other particulates and joints are required approximately every 20 metres.

8.4 High Temperature Superconducting cables (HTS) [10]

Power cables based on the HTS materials can offer several advantages compared to conventional power cable technology due to the unique properties of the HTS material, the needed internal cooling and a perfect magnetic shielding (for some designs). The advantages of an HTS power cable are:

- High current and power rating
- Compact cable dimensions
- Low losses (less than 1%, compared to 5% to 8% for traditional cables)
- No thermal interaction with the surroundings
- No magnetic interaction with the surroundings

The main disadvantage to date has been the high cost of HTS wire. The wires used for conventional conductors for electricity transmission and distribution are usually made from copper or aluminium and the present cost for copper wire is approximately $10 per kAm and $2 per kAm for aluminium wire.

In contrast, commercial HTS wire (which is made of bismuth strontium calcium copper oxide) costs around $200 per kAm.

IX. MAINTENANCE CONSIDERATIONS

Overhead lines do require more maintenance than cables. Amongst conductor, hardware, structure and foundation inspections, long-term maintenance of overhead lines includes the measurement of tower earthing. Overhead lines without an overhead shield wire are simpler to measure than overhead lines with towers connected together by the shield wire.

When overhead towers are connected together by means of an overhead shield wire (or counterpoise earth), all of the earth resistances are in parallel. Measurement under conditions provides an overall value of the earth resistances of all towers from the point of measurement and not the earth resistance of a particular tower.

X. DISCUSSION

The following discussion considerations, taken from reports produced by utilities and from conversations with industry experts, provide additional information on the reliability characteristics of overhead and underground power lines: [5]

- Overhead lines tend to have more power outages primarily due to trees coming in contact with overhead lines.
- It is relatively easy to locate a fault on an overhead line and repair it. A single line worker, for example, can locate and repair a fuse. This results in shorter duration outages.
- Underground lines require specialized equipment and crews to locate a fault, a separate crew with heavy equipment to dig up a line, and a specialized crew to repair the fault. This greatly increases the cost and the time to repair a fault on an underground system.
- In urban areas, underground lines are four times more costly to maintain than overhead facilities.
- Underground lines have a higher failure rate initially due to dig-ins and installation problems. After three or four years, however, failures become virtually non-existent.
- As underground cables approach their end of life, failure rates increase significantly and these failures are extremely difficult to locate and repair. Maryland utilities report that their underground cables are becoming unreliable after 15 to 20 years and reaching their end of life after 25 to 35 years.
- Pepco found that customers served by 40-year-old overhead lines had better reliability than customers served by 20-year-old underground lines.
- Two Maryland utilities, Choptank and Conectiv, have replaced underground distribution systems with overhead systems to improve reliability.
- Water and moisture infiltration can cause significant failures in underground systems when they are flooded, as often happens in hurricanes.
- Due to cost or technical considerations, it is unlikely that 100 percent of the circuit from the substation to the customer can be placed entirely underground. This leaves the circuit vulnerable

to the same types of events that impact other overhead lines, e.g., high winds and ice.

The installation of partial or complete underground cabling is a result of significant system planning and operational implications. Traditionally, technical limitations and cost factors of cable installations have been major considerations for installing cables. Additional considerations are: application and planning considerations; environmental constraints, comparative investments, and perspectives. It is generally unlikely that 100 percent of the electrical network can be placed entirely with underground cable. This leaves a portion of the circuit vulnerable to the same types of events that affect overhead lines, e.g., high winds and ice.

There are, however, other substantial benefits for burying existing overhead power lines, the most significant of which is improved aesthetics. Many communities and individuals want their power lines removed from sight. While the benefits derived from these kinds of undergrounding initiatives are difficult to quantify, they are real and they are substantial. Because these projects cannot be justified based on standard economic criteria, community and government decision makers often struggle to determine who should pay and who should benefit from undergrounding initiatives based on aesthetics.

XI. CONCLUSION

From a financial balance sheet point of view, overhead lines remain the most used means for electricity transmission. This is due to their lower capital cost in comparison to underground cable. The difference of costs between underground cable and overhead lines is still high and will remain, unless a future mass production of cables reduces their construction cost.

Furthermore, when comparing the various types of underground cable, XLPE cables are generally considered to be the cheapest and most developed cable technology compared to GIL cables. These are to be used in special cases of short distances and when high load levels are present. In addition, the HTS option is still in R&D prototype stage and will need a number of years before they become commercially available on a large scale.

Generally, underground cables are applied in special cases, such as in urban areas and sensitive ecological, aesthetic or historical areas, or where the security of supply is in danger due to frequent adverse weather conditions.

From a technical balance sheet perspective, overhead lines offer the greatest benefit for upgrading. Furthermore, maintenance skills are generally readily available as opposed to EHV cable jointers. Fault location for cables is specialised and time consuming. Environmental risks on overhead lines depend on the terrain, weather conditions and public opinion towards overhead lines.

Decision making based on technical balance sheet will primarily be based on the ratings of the individual risk factors in *eq. 4, i.e.* $R_e = k_1.E_o+k_2.U_p+ k_3.R_f+ k_4.R_u+ k_5.S_d+ \ldots$

REFERENCES

1. UCTE *Comments on the background paper undergrounding of electricity lines in Europe commission of the European communities* Brussels, 10 December 2003.
2. Johnson, A.J., & Wichern, D.W. (2002). *Applied Multivariate Statistical Analysis* (5th Edition). Apprentice Hall, New York.
3. Gorsuch, R.L. (1983). *Factor analysis* (2nd Edition). Hilldale, NJ: Erlbaum.
4. Brakelmann, H., Jensen, H., *"Three-phase single-core cable system with core-redundancy"*, University of Duisburg-Essen GEO mbH, Energy-Transport and -Storage Enge-Sande.
5. ICF Consulting Ltd, "*Overview of the Potential for Undergrounding the Electricity Networks in Europe"* Prepared for the DG TREN/European Commission, United Kingdom, February 2003.
6. Johnson, B.W., *Out of Sight, Out of Mind? A study on the costs and benefits of under grounding overhead power lines*, Edison Electric Institute, July 2006.
7. IEC 289, *"Reliability based design methods for overhead lines advantages, applications and comparisons"* Study Report of Working Group B2.06, April 2006.
8. *Risk Management Solutions, March 2006 "U.S. and Caribbean Hurricane Activity Rates."*
9. Koch, H., *Experience with 2nd Generation Gas-Insulated Transmission Lines GIL*,

Siemens AG, PTD H 2S Paul-Gossen-Straβe, Germany.
10. http://www.sei.co.jp/super/cable_e/albany.html.