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Comparative Analysis of Cost between EHV AC Overhead Transmission Lines and Underground Transmission XLPE Cables

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Abstract: This article compares the overall lifecycle costs of Overhead Transmission Lines (OTL) and Underground Transmission Insulated cables (UTC) of 220 KV. In this article present value of periodical maintenance, loss of energy and dismantling cost of transmission lines is taken into account while calculation of lifecycle cost. Also in this article social cost arises from overhead transmission line and underground cable is taken in account while compare the entire service life of the transmission line. The entire procedure is shown by carrying out on average market value of cable and overhead lines. All operating costs over the life of the asset can be converted into an equivalent capital sum at the start of the project life and so these costs can be added to the capital cost of the investment. In addition to the economic costs, this article also quantifies the environmental costs of a transmission facility, in terms of the burden on the built/developed/occupied land or territory. The presence of an electro-magnetic field exceeding the value set by national Laws (or Rules or Standards) may create a quarantined area of land unavailable for human activities or development. Nonetheless, the method may be widely applied to any type of OTL UTC comparison.

Keywords: Transmission Lines, Underground Transmission Cables (UTC), Overhead Transmission Lines (OTL), Economic comparison, Lifecycle cost.

I. INTRODUCTION

The first 220 kV XLPE UTC and accessories with silicone rubber insulation bodies were installed in the network at the beginning of the year 1984. With the market introduction of cross-linked polyethylene (XLPE) extra-high voltage (EHV) cables, the high investment costs of EHV Underground Transmission Insulated Cable (UTCs) (which can be increased by shunt reactive compensation) were often taken as an argument to prefer an OTL “a priori,” without consideration of the sensibly different economic burden brought about by OTLs. Meaningful differences concern the impact of a new line on territory and the energy losses over the lifetime. The role of these factors has gained importance in recent years because of safety and ecological increasing constraints on territory and more stringent grid energy-efficiency requirements. Consequently, suitable criteria were introduced into the economic analysis in order to evaluate costs and benefits emerging from these issues for the two alternatives. Below shows the major cost component over the entire service life of transmission lines.

- Capital costs (I);
- UTC shunt compensation investment cost(C);
- Loss energy costs ((E));
- Burden on territory (T);
- Dismantling costs ((D));
- Operation and maintenance costs ((OM)).

From last two decades there is continuous improvement in XLPE insulated cable technology which re-focused attention towards the installation of underground HV and EHV transmission lines. The deregulation of energy market and the need to connect new power plants to the existing grid has further stimulated the growing requirements to install a significant quantity of underground cables. In the near future, in order to sustain the transmission grid development, a comparative economic analysis of innovative and traditional transmission lines will be essential. The planning choices will have to be consistent with safety, reliability and operation constraints, taking into account the transmission costs. The choice between the two solutions AC OTL and underground cable UTC is merely driven by technical, environmental, and economic considerations. In this article, the analysis has been focused on and restricted to AC underground transmission cables and overhead transmission lines. The article compares costs of overhead lines and underground XLPE cables, both being possible options for the construction of new lines in existing grids. All operating costs over the life of the asset can be converted into an equivalent capital sum at the start of the project life and so these costs can be added to the capital cost of the investment.

In addition to the economic costs, this article also quantifies the environmental costs of a transmission facility, in terms of the burden on the built/developed/occupied land or territory. The presence of an electro-magnetic field exceeding the value set by national Laws (or Rules or Standards) may create a quarantined area of land unavailable for human activities or development. The economic impact (€/m^2) to the land crossed by a transmission line can be estimated taking into account the loss of value of the rights-of-way. The methodology can be applied, modifying its constituent parameters, to many different configurations and countries.

II. UNDERSTANDING TRANSMISSION COSTING FACTORS

For an OTL, the number of conductors per phase, the type of conductor and the type, size and height of tower, depend on technical requirements and geographical factors that perhaps vary from country to country [2]. In order to show the application of the present comparative procedure, a real example has been chosen but the procedure can be applied to any configuration. Therefore, the economical comparisons have been computed for the HV voltage levels. Fig. 1 shows the standard towers at 220 kV, reporting clearances of the conductor spacing necessary for positive-sequence(inductance and capacitance) parameter computation and the minimum clearances above ground H_{min} used in computation of rights-of-way (with reference to a given target of quality of magnetic induction level and rms current value). In general, each country has its own H_{min} it is around 6.82 -7 m for 220 KV OTL. In this article, the traditional towers only are considered even if an overhead line could be erected with more innovative design (compact towers, Foster type etc).

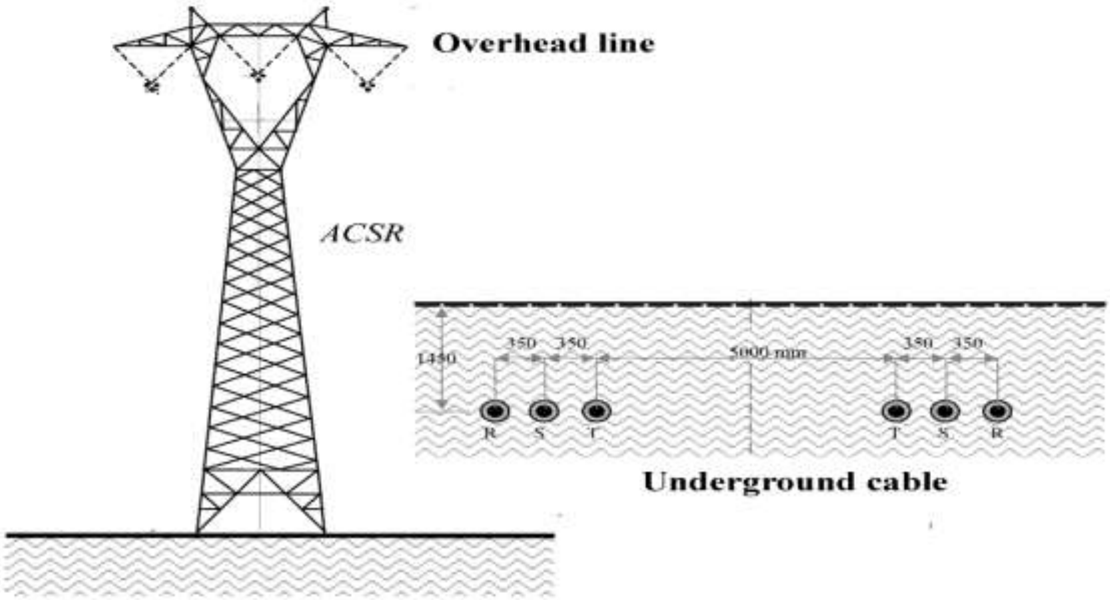

Fig. 1 shows the 220 kV OTL & UTC

For the HV level of 220 kV, the OTL is equipped with the same phase conductor ACSR Φ=31.5 mm as it appears suitable for a new line. With regard to the 220 kV cable system, Fig.1 also shows the typical underground installation of a double-circuit UTC with 2500 mm^2 copper conductors, necessary to transmit the same ampacity of a single-circuit OTL 3x585 mm^2. In fact, the last row of Table I report the ampacity for OTL i.e. the thermal limiting current of a line. The 220 kV UTC configuration is usually flat type (even if trefoil ones are usually adopted) where the spacing and burial depth (from cable axis) reduces to 165 mm. IEC 287-3-1 reports the different country standards but the values do not differ significantly from those chosen. Table I reports positive-sequence parameters per unit length in order to compute the steady-state regime and power losses of the distributed parameter line. These losses are the sum of Joule and shunt conductance losses. In the sinusoidal regime, the OTL conductance is usually neglected but in this case consideration is taken of the corona losses and the insulators leakage currents. Both types of loss depend upon the prevailing weather conditions (dry or rainy) and, for instance, 90 rainy days per year have been considered. The per unit length resistance of OTL has been computed at 75°C, conductor temperature when operated at the thermal limit (depending upon room temperature and wind conditions, etc). The electrical parameters of the cables have been computed by means of IEC 287 assuming perfect cross-bonding (i.e. no induced current) at a given spacing, which determines both the inductance and the apparent resistance parameters and consequently all the transmission constants.

It is worth noting that the cable ampacity evaluation is performed according to the thermal study affected by, beyond the cable spacing, soil (ρ=1.0 K·m/W for other country's values refer to IEC 287-3) and cable thermal resistivities as well as the burial depth.

TABLE I

OVERHEAD #			CABLE #		
Voltage level	220 kV		Voltage level	220 kV	
Conductor diameter	ACSR Φ=31.5 mm	mm^2	Cross-section	Φ=1600 Al	mm^2
Resistance at 75°C (50 Hz)	69.3	mΩ/km	Apparent resistance at 90°C (50 Hz)	32.6	mΩ/km
Per unit length series inductance	1.282	mH/km	Per unit length inductance	0.480	mH/km
Per unit length shunt Leakance (50 Hz)	20	nS/km	Per unit length shunt Leakance (50 Hz) with tanδ = 0.0007	53.0	nS/km
Per unit length capacitance	0.00894	µF/km	Per unit length capacitance with ε_r=2.3	0.241	µF/km
Ampacity	905	A	Ampacity	1089	A

A. OTL AND XLPE UTC CAPITAL COSTS (I)

The uncertainties associated with capital costs of innovative technologies does influence the comparative evaluation results. The necessity to adopt a methodology that takes into account the technical, environmental and social aspects involved in new line realization should be noted. The choice of parameters can vary country by country but the methodology and approach remain the same. The UTC capital cost includes the burden for excavation and installation, whereas in the case of OTL the cost burden of the wayleave is considered. The investment costs of UTC are not proportional to line length due to the fix costs of terminal stations. The line lengths in the article are typically longer than 5 km and hence capital cost can be considered a length linear function. The capital expenditure (*Capex*) for a new transmission line can be assigned to one or more construction years, preceding the start of circuit operation. In the present case, it has been assumed that all investment costs (I) were sustained in the construction year 0.
The main cost components are:

- cost for acquisition of rights of way (*ROW*s);
- cost for acquisition of further portions of land (e.g., for location of substations) from land owners;
- cost of purchase of all pieces of equipment from manufacturers;
- costs for transportation of materials;
- costs of onsite civil and electrical works for equipment installation;
- cost of civil works (for example: towers foundations and trench excavation);
- costs for swathe reinstatement at the end of construction works;
- contingency costs, which account for the risk of sustaining extra costs not precisely identifiable in the project economic appraisal;
- Engineering and project-management costs.

It is worth noting that the cost figures used in the following calculations are rough approximations and do not refer to any specific project. They represent mean reference values resulting from worldwide industry surveys: the actual costs for each particular project can change sensibly with local market situations and commercial agreements. The following *Capex*s have been assumed for the transmission lines in Fig. 1.

TABLE II

	Capital cost of OTL (I) (M€/Km)	Capital cost of UTC (I) (M€/Km)
At 220KV	**0.385**	**3.1**

Ratio of UTC/OTL = 8.05. Therefore cost of UTC is approx 8 times compared to the cable.

B. THE COST OF REACTIVE COMPENSATION(C)

In the case of construction of long UTCs, an additional cost for the provision of reactive power compensation must be accounted for. In the proposed cable circuit, two shunt reactors, one at each cable end, must be foreseen. The suitable value of the compensation degree is equal to 0.53 is taken through out in this paper. The investment costs for reactive power compensation include:

- The acquisition costs of the land where each reactor (usually three phase with unchained magnetic flux) and its dedicated surge arresters, circuit breakers, earth switches, and disconnecting rods will be located;
- The costs for site preparation and other civil works;
- The supply capital cost of the aforementioned equipment;
- The equipment installation work costs.

One part of the investment cost must be sustained regardless of the amount of inductive reactive power needed, it represents the constant portion of the reactive compensation capital expenditure. The remaining part is variable and mainly linked to the size of reactors. It may be assumed proportional to the provided MVaRs. The entire compensation power needed for the double-circuit line of Fig. 1 (with 0.53), can be estimated to be about. Table 3 shows the required compensation cost for UTC.

$Q_c = w \times C \times U_m{}^2 = 2 \times 3.14 \times 50 \times 241 \times 220^2 = 3.66$ MVaR/Km;
$Q = K \times 3.66 \times 2 \times L = 96.99 = 0.53 \times 3.66 \times 2 \times 10 = 38.796 =$ approx. 40MVaR;
Where K is compensation factor, w is angular frequency, U_m is nominal voltage;
(Q) = (40 × 17.5)/10 = 0.07 M€/Km.

TABLE III

	Capital cost of OTL (M€/Km)	Capital cost of UTC (M€/Km)
Investment Cost At 220KV	**0.385**	**3.10**
Compensation cost	**NIL**	**0.07**

C. POWER LOSSES EVALUATION ((E))

The economical assessment of the power losses plays a significant role in the overall cost evaluation during the operational life of a transmission line. The load diagram of a line is strictly linked to its typology. There could also be cross-border interconnections, connections between power plant and grid [1] or lines in the meshed transmission network. With regard to the latter, the load diagram presents great fluctuations both on a daily and monthly basis. By analyzing some HV line load diagrams, an equivalent operation at the maximum power with cos ϕ =0.98 for 350 hours a year has been considered. If the line is directly linked to a power plant, the load profile depends upon the power generation profile (base load and peak load power plants). In these cases, the power loss economic evaluation can play a more relevant role [1]. Therefore, it is possible to compute the energy losses for two different transmission technologies with the same length **L** and the corresponding actual costs (V_{OTL} for OTL and V_{UTC} for UTC) in the following hypotheses:
Line lifetime = 40 (years);
Real rate of interest (discount rate) = 5%;
Loss energy cost = 40 (€/MWh).
Therefore Annual Energy Loss (AEL) = 7096 Kwh/Km for UTC while AEL for OTL = 14980 Kwh/Km.

$$((E)) = \frac{(1+i)^n - 1}{i(1+i)^n}(AEL \times cost\ of\ power)/l \quad [8]$$

where i = 5% & N = 40 years hence calculating, we have **((E)) = 0.4870 {M€/Km}** for UTC while **((E)) = 1.0282 {M€/Km}** for OTL. Where cost of power taken as 40 Euros/MWh & l = length of line.

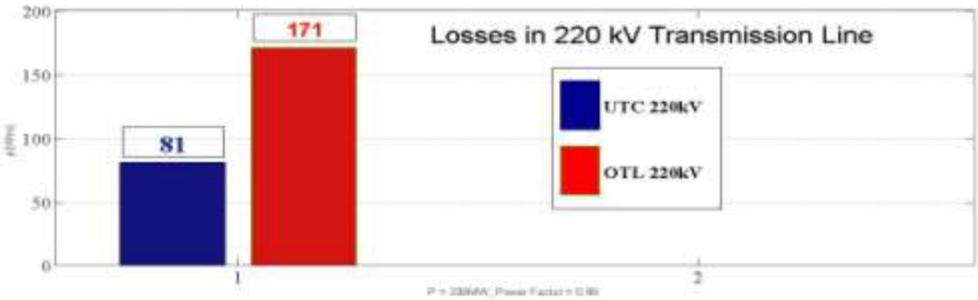

Fig. 2 (Bar chart) shows the losses for OTL and UTC

TABLE IV

	Power Losses of OTL ((E)) (M€/Km)	Power Losses UTC ((E)) (M€/Km)
At 220KV	1.0282	0.4870

Fig. 2 shows the power losses for EHV-HV voltage levels. Table IV shows the present value of losses which occur in entire service life of transmission line. The dielectric UTC losses vary from 1.0 % (132 kV) to 4.4 % (380 kV) of total whereas for OTL they are noticeably lower (0.26, 0.56, 0.44 % for 380, 220 & 132 kV respectively).

D. THE BURDEN ON TERRITORY OR LAND (T)

The actions of each country to mitigate against exposure to electromagnetic fields differ. For example, the framework law has imposed a general discipline devoted to protection from electromagnetic field exposure [3]. Conservatively, it is possible to determine a right-of-way, where any building activity is interdicted to extended residence, along all the AC transmission line route, having a width F depending upon current, voltage limit and line arrangement. The right-of-way is wider or shorter as a function of the magnetic induction limit of exposure and hence of the maximum current. Usually for existing lines, there is a value of attention of 10 µT whereas for new lines a target of quality of 3 µT. It is noted that the magnetic field as well as the right-of-way for UTC perhaps be reduced by the phase cable arrangement and/or screening. In order to quantify the cost burden of land or territory due to the installation of a new line, UTC and OTL are considered to be erected on the same route and on land that has not been developed/built in but with a "buildability" similar to that of the area adjacent to right-of way. It is necessary to evaluate the loss of value of the land due to difficulty or prohibition of future development as a result of the presence of the transmission line. To this end, it is proposed that a suitable building coefficient "ed" be assumed that is determined and is consistent with adjacent area to new line right-of-way. The parameter ed (m^3/m^2) is highly variable as a function of geographic situation and means the average ratio, in a given area, between building volume and surface of area itself; it ranges between 3-4 in urban area and 0.8 - 1 in suburban area. In order to evaluate the variation of value of land located in the rights-of-way, it is necessary to know some parameters depending upon the land kind. Therefore, every square-meter of land located in the "rights-of-way" would lose: $w_x = k \cdot ed$ (€/m^2), where k (Euros/m^3) is strongly dependent on the local real estate market. Hence, the burden on an area of extension F {1000 sq. meter}, (that is, the width of the no-build band multiplied by an unitary kilometric length of "corridor") can be written as

$$(T) = F \times 10^{-3} \times w_x$$

In the OTL case, with the value 48m and for UTC it is just 4m, resulting from electromagnetic-field (EMF) calculations and compliance with the quality target limit along different Europe countries, it yields

$$(T) = 0.004 \times w_x \ \{M€/km\} \text{ For UTC}$$

$$(T) = 0.048 \times w_x \ \{M€/km\} \text{ For OTL}$$

TABLE V

	Burden On Territory For OTL (T) (M€/Km)	Burden On Territory For UTC (T) (M€/Km)
At 220KV	$0.048 \times w_x$	$0.004 \times w_x$

E. THE VISUAL IMPACT

The economic evaluation of visual impact is extremely complex owing to its strongly subjective nature (as the value of the landscape is something very specific and a function of local views and preferences). Not withstanding the ambiguity, when a new line must be installed, this aspect could be evaluated. In this respect, the advantage of UTC is understandable.

F. DISMANTLING COST ((D))

A comprehensive analysis of a transmission line must take into account the end of life i.e. the dismantling phase of the line. This operation foresees some costs in order to restore the place at the end of line life, with a considerable delay with respect to the investment and a subsequent lower burden [1]. Dismantling & decommissioning cost is taken as 5 % of total cost of investment for OTL & UTC. Table VI shows the present value of cost of dismantling a transmission line.
For UTC

$$((D)) = \frac{0.05 \times 3.17}{(1+i)^n}$$

For OTL

$$((D)) = \frac{0.05 \times 0.385}{(1+i)^n}$$

Where i = 5% & N = 40 years life, hence calculating, we have **((D)) = 0.0225 {M€/Km}** for UTC while ((D)) = **0.00273{M€/Km}** for OTL.

TABLE VI

	DISMANTLING COST OTL ((D)) (M€/Km)	DISMANTLING COST UTC ((D)) (M€/Km)
At 220KV	**0.00273**	**0.0225**

G. OPERATION AND MAINTENANCE ((OM)) COSTS

The operation and maintenance of a line, during its life, implies some costs. They must be considered in the overall cost analysis. The evaluation of OM refers to investment cost per kilometer the following values represent the annual cost to pay per kilometer of line as a percentage of investment cost as sown in table VII. For an OTL, the maintenance costs are between 0.7 and 1% a year (with respect to investment costs) and depend upon the weather conditions. The OTL operation ranges between 0.8 and 1%. The OTL OM (flat installation with low salt pollution) can range between 1.5 and 2%. These values must be considered as an average indication and can rise in cases of extraordinary environmental occurrences. With regard to UTC, once installed, they do not need particular maintenance due to the absence of atmospheric external situations. The UTC maintenance can be evaluated as 0.1 % of the capital cost. The procedure does not take into account the different failure repairing times of OTL and UTC and their influences on the system costs.

TABLE VII

Table (OM) cost of UTC & OTL [5]		
	OTL	UTC
Operation	0.8 – 1.0%	0.1 - 0.3%
Maintenance	0.7 – 1.0%	0.1%
Operation & Maintenance cost	1.5 – 2.0%	0.2 – 0.4%

For UTC

$$((OM)) = \frac{(1+i)^n - 1}{i(1+i)^n}(OM)$$

For OTL

$$((OM)) = \frac{(1+i)^n - 1}{i(1+i)^n}(OM)$$

TABLE VIII

	OPERATION AND MAINTENANCE ((OM)) COSTS of OTL (M€/Km)	OPERATION AND MAINTENANCE ((OM)) COSTS of UTC (M€/Km)
At 220KV	**0.033033**	**0.029918**

Where i = 5% & N = 40 years hence calculating, we have **((OM)) = 0.029918 {M€/Km}** for UTC while **((OM)) = 0.033033 {M€/Km}** for OTL. Table VIII shows the present value of the operation and maintenance cost of transmission line.

III. TRANSMISSION LINE COST ANALYSIS

From Table IX (reporting all of the aforementioned cost components), it can be seen that the proportion between the ratio involving only the initial investment costs for the UTC and the OTL cases i.e., Ratio of UTC/OTL = 8.05 and that embracing, instead, the whole-of-life costs (yet leaving out the cost components (T) for OTL and UTC), ratio of lifecycle cost of UTC and OTL is 2.56, decreases by a factor of 5.49. Savings from lower UTC energy losses chiefly contribute to this change.

TABLE IX

	OTL {M€/Km} at 220 kV	UTC {M€/Km} at 220 kV
CAPITAL COST(I)	0.385	3.10
COMPENSATION COST(C)	0.0	0.07
POWER LOSSES	1.0282	0.4870
BURDEN ON TERRITORY FOR OTL ((T))	$0.048 \times w_x$	$0.004 \times w_x$
DISMANTLING COST OTL ((D))	0.00273	0.0225
OPERATION AND MAINTENANCE ((OM)) COSTS	0.033033	0.029918
(∑) Total:	$1.448963 + (0.048 \times w_x)$	$3.709418 + (0.004 \times w_x)$

The other, potentially relevant, factor further lessening the proportion between overall UTC and OTL costs is the lighter economic burden on territory imposed by the installation of a cable as an alternative to an overhead line. If there are restrictions of land use because of local laws, the amount of these compensation costs (T) (appearing in Table V as a function of w_x) depends on the market value of the land crossed by the link. In the hypothesis of build-prohibition all over the width of the corridor where the magnetic field magnitude exceeds 3μT, Fig. 3 shows the overall costs and as a function of w_x. The intersection point between (∑) of UTC and OTL (whose abscissa w_x = **51.37** Euros/m^2) is the point of economical indifference.

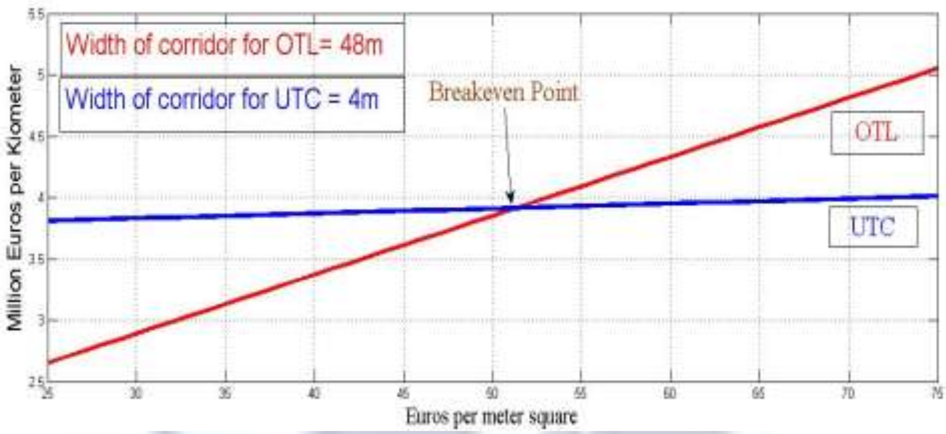

Fig. 3 overall cost per kilometer as a function of w_x ("quality target" = 3 μT)

IV. CONCLUSION

This paper presents a unique method for the identification and calculation of deterministic components of the whole of life cost of OTLs and of XLPE UTCs. Ensuring reliable and economic connections and respecting the environment is a crucial task, often requiring innovative solutions. Whereas overhead lines have been the selected solution, extra high voltage cables have made a breakthrough with the introduction of XLPE insulation reducing dramatically the losses whilst maintaining an excellent level of cable system performance. In spite of the low investment cost of overhead lines, UTCs have other important tangible benefits as well as some advantages which are less tangible. This paper makes a detailed technical and economic assessment of these two different technological solutions. The model however can be applied to any country with its own specific transmission standards, rules and/or laws. Drawing some general conclusions, it is apparent that where land has already been developed for residential purpose or where development potential is very high, underground cables are preferred option having less environmental impact even if there are higher capital costs. Conversely, in low value territory, transmission technologies with higher territory impact and fewer capital costs are preferable. In conclusion, overhead lines and cables have been debated as competitors often without stating precise criteria. From an overall cost standpoint and not from a mere investment cost standpoint, the cost gap between UTCs and OTLs is strongly reduced due to UTC energy loss savings and a lower impact on territory. One another aspect of this article is compensation for acquiring right of way for transmission line can be easily obtained. For the sake of simplicity, the procedure does not take into account the costs due to undelivered energy nor the congestion and re-dispatching costs arising from the differences in UTC and OTL failure repair times.

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