Electricity Transmission

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Energy Systems

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Introduction

To provide the inhabitants of the island at study access to electricity, a transmission grid must be established. This grid must not only be extensive enough to aggregate all the 50 000 inhabitants, but also stable to ensure that blackouts are easily avoided.

This transmission can be made in alternate current (AC) or direct current (DC), through underground or aerial infrastructures. Based on the characteristics of each option, it will be determined which option is more adequate for our island.

It will also be determined how extensive the grid should be, meaning, how much customers can there be for each kilometre of transmission line. This will depend on the population density of the island. Once the extension of the grid is established, an analysis of the losses and costs can be made.

AC vs. DC Transmission

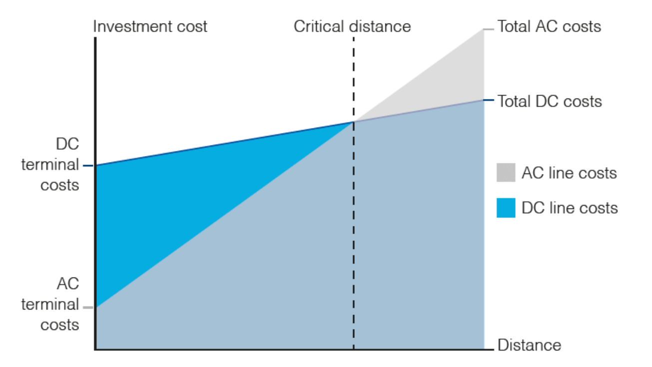
Every transmission system is different. Each one is studied before to make sure it suits the needs of the systems according to distance, power, environment, etc.

The first topic of our study in designing a transmission system is about using alternating current or direct current. Let us see the differences between them in general.

Alternate current transmission lines have a higher cost of investment. The overall efficiency of the transmission is lower, due to the skin effect (alternate current flows through the surface of the conductor, which increases the resistance of the material). The regulation of the voltage is more complicated and there are more interferences in comparison with direct current. However, the increase of voltage is much easier and more efficient, and the maintenance is also easier and generally cheaper.

Direct current transmission lines are cheaper and easier to build. They require less material (only one or two conductors, no transformers) and have no issues regarding inductance, capacitance, phase dislocation, stability or synchronization. It does not suffer of the skin effect as that only applies to AC, making it more efficient and its lines require less isolation. The regulation of voltage is much easier in this option. However, contrary to AC, in DC electricity cannot be generated at high voltage, neither can voltage be increased. In addition, repairing and maintenance is rather expensive and difficult.

Therefore, in general, it is preferred to adopt a high voltage DC transmission. This can be achieved by using rectifiers and inverters to convert AC into DC and vice-versa easily and efficiently. The present-day trend is towards AC for generation and distribution and high voltage DC for transmission.



Graph 1 - Costs of AC and DC relative to distance and critical distance which is around 500 to 600 km.

However, the island that we are studying is quite small (if we consider it as a circle, it would have a perimeter of only 250 km), which makes us choose AC transmission for this case, due to the image on the side, but only for on land transmission. In case of offshore production, the type of current would have to be restudied according to the distance between the island and the power source.

Overhead vs. Underground Transmission Cables

The electricity in the island is mostly supplied by renewable sources which are generally located far from the residential region. This means that there will be a wide transmission grid and with the question of what sort of cable positioning is more adequate: overhead or underground.

Overhead or aerial transmission lines are the most common. This is mostly due to the fact that it is the cheapest option. It is also less invasive in terms of construction as very little destruction is required to set it up. However, these infrastructures are somewhat fragile, as they are more susceptible to weather conditions such as severe storms and their consequences (floods or felling of trees). This can possibly cause blackouts. Nevertheless, when there is a problem in the infrastructure, it is easier to identify and fix, with this process usually taking only a few hours. It also affects the lifespan of wildlife such as birds, squirrels, and other small rodents. In addition, there is a significant visual impact and noise which aggravates once it starts raining.

Underground transmission lines are much rarer, as it has a very high investment cost, being about 10 to 15 times more expensive than overhead lines. The construction process is environmentally impactful as it requires digging large amounts of land to ensure that the lines are well isolated. However, this isolation makes this option generally safer for both wildlife and humans, with less transmission losses, without visual impact and completely silent. Nevertheless, it is a lot harder to identify and correct possible issues, which can cause partial or total blackouts for undetermined amounts of time (sometimes up to days). In terms of lifetime expectancy, underground transmission lines usually last about 40 years, which is half of the 80 years expected of overhead lines.

Since the maintenance of underground transmission lines is much harder and more time consuming, which can be highly problematic in an island scenario where stability of supply is essential, overhead transmission lines seem to be more adequate in this case. However, there are exceptions to this choice, these being airports, offshore production and urban areas, in which these are already commonly used.

Case study: Our Island

Since we are scaling the extension, the losses and the costs associated to the transmission grid of an isolated Island without having access to similar cases in other regions we had to estimate these factors based on comparing ratio. In order to do that, we chose a region with similar characteristics, the island of Madeira.

From PORDATA and Wikipedia, we got the information regarding Madeira Island's population in 2019 (the earliest data available) and area, respectively. With these two values we computed the population density, the ratio between the inhabitants and the region's area. The square one information regarding the study is already known for both islands, and it is summarized in the following table.

	Madeira	Our Island
Area [km²]	741	500
Population	249 052	50 000
Population density [inhabitants/km²]	336	100

Table 1 - Madeira and our Island's initial data.

For both islands, the areas are quite comparable, Madeira's population is almost five times our Island's population, and the population density of Madeira is almost three and a half times the value for our Island. With these data we were able to calculate three different dimensioning ratios between the two islands:

$$Area\ Ratio = \frac{Our\ Island's_{Area}}{Madeira\ Island's_{Area}} = \frac{500}{741} = 0{,}675$$

$$Population\ Ratio = \frac{Our\ Island's_{Population}}{Madeira\ Island's_{Population}} = \frac{50\ 000}{249\ 052} = 0{,}201$$

$$Population\ density\ Ratio = \frac{Our\ Island's_{Population\ density}}{Madeira\ Island's_{Population\ density}} = \frac{100}{336} = 0{,}298$$

Transmission Grid extension

The first part to be dimensioned in our case study is the electricity transmission and distribution (T&D) lines. From an Eletricidade da Madeira's report we found the detailed characterization of the T&D grid, the existing length for high, medium, and low voltage cables (from now on mentioned as HV, MV and LV, respectively).

To calculate the length of the LV cables in our island we multiplied the equivalent data from Madeira by the Population Ratio, because these cables are more suited for electricity distribution in houses. The length estimation for the MV cables was made by multiplying the equivalent data from Madeira by the Population density ratio. Finally, to obtain the length of the HV cables, we multiplied the equivalent data from Madeira by the Area ratio, because these cables are more suited for electricity transportation between the electricity producers (power plants) and the distribution grid (MV and then LV).

Voltage transformers make possible the connection between transmission lines with different voltages, that means the transition between HV, MV and LV lines. To estimate the number of voltage transformers needed to install in our case study we multiplied the number of the ones installed in Madeira and multiplied by the Population density ratio.

With the three ratios defined above, our Island's grid is estimated to be the following:

Length [km]	Madeira			Our Island		
	Over head	Under ground	Voltage Total	Over head	Under ground	Voltage Total
LV	3 875	2 104	5 977	778	422	1 200
MV (6,6 and 30 kV)	593	903	1 496	176	269	445
HV (60 kV)	75	27	103	51	18	69
Type Total	4 543	3 034	7 576	1 005	709	**1 714**
Number of Voltage Transformers	47			**14**		

Table 2 - Transmission and Distribution lines characterization for Madeira and our case study Island's.

With a total extension of 1 714 km of electricity T&D lines estimated for our Island, we can predict the number of customers served by a single kilometer of line:

$$Customers\ per\ line\ km = \frac{50\ 000}{1\ 714} = 29{,}2$$

Electricity losses in transport and distribution

Still from Eletricidade da Madeira's report, the losses in the electricity (T&D) in 2020 reached 8,3% of the total electricity introduced in the transmission grid. We decided to assume the same value for our case study, as percentages do not change.

From the Electricity Demand report, the electricity consumption relies on 248 000 MWh per year, and, as this consumption is the one given to the consumers, $248\ 000 \times (1 + 8{,}3\%) = 268\ 584$ MWh/year is the actual electricity that enters in the T&D grid. From this electricity, 20 584 MWh are lost in the lines during the T&D process.

Costs

After gathering all the information that describes our case study's grid, comes the estimation of the costs needed for this infrastructure.

Installation costs

The Portuguese legislation sets the cost per meter for the overhead and underground lines and by voltage, so there are three different costs defined for LV installation (set for three different intervals of required power) and only one cost defined for MV installation (set for any required power). The unitary cost for the low voltage is an average of the 3 given values, as we still do not know the required power to be installed. The high voltage comes from a ratio between the HV and MV costs, taken from a previous Electricity Transmission report; this ratio helped us to predict the HV unitary cost, as we had no access to a specific cost regarding the high voltage. The unitary cost for medium voltage is simply the value we got from the Portuguese legislation.

The summary of the costs is presented in the next table:

Cost [€/m]	T&D lines installation costs (ERSE)	
	Overhead	Underground
LV	9,59	24,20
MV (6,6 and 30 kV)	24,78	52,90
HV (30 kV)	20,76	49,21

Table 3 – Unit length costs for the transmission and distribution lines with different characteristics.

The Voltage Transformers we assumed to be the same as mentioned in a master thesis, costing around 1,15 M€/unit.

With the already known line extension and the amount of transformers required, the following investment will be needed:

Cost [M€]	T&D lines installation costs for our Island		
	Overhead	Underground	Voltage Total
LV	7,46	10,22	17,69
MV (6,6 and 30 kV)	4,37	14,21	18,58
HV (30 kV)	1,05	8,97	1,95
Type Total	12,89	25,33	**38,22**

Table 4 - Total costs for transmission and distribution lines.

The 14 Voltage Transformers will cost, in total, around 16,1 M€.

Operation and Maintenance costs

Apart from the investment costs, we must consider the operation and maintenance (O&M) ones as well. An identical method was applied for these costs.

Starting with the annual unit length costs with overhead and underground lines:

[k€/line km per year]	Overhead	Underground
O&M costs	9,05	10,77

Table 5 - Annual costs per line km for operation and maintenance.

Applying the costs for the line extension we get:

[M€ per year]	Overhead	Underground	Total
O&M costs	9,10	7,64	**16,74**

Table 6 - Total annual operation and maintenance costs.

Economic Analysis

To complete the economic analysis, it was considered an average life cycle (N) of 30 years and a discount rate (d) of 5%.

The total initial investment is the sum of the costs related to the T&D lines and the Voltage Transformers:

$$Initial\ investment = T\&D\ lines_{\ installation\ costs} + Voltage\ Transformers_{costs}$$

The 30 years operation and maintenance costs were set to a present value using the proper equation: $O\&M_{N\ years} = O\&M_{annual} \times \frac{(1+d)^N - 1}{d \times (1+d)^N}$.

The total costs can be normalized in respect to energy and in respect to both energy and length, as shown in the next table.

Initial investment [M€]	O&M costs [M€]	Total costs [M€]	LCOE [€/kWh]	LCOE [€/kWh per line km]
54,32	257,30	**311,62**	**0,04**	**2,44 × 10^{-5}**

Table 7 - Economic analysis for the case study.

Conclusion

According to what was mentioned previously, the HVAC transmission is the best fit for the grid since the island at study has a relatively reduced area. In addition, overhead transmission lines are the best answer to the consumption needs as they provide more stability, a lower cost of installation and easier and faster repairs. This has a few exceptions: some urban areas, offshore production, and airport zones.

Regarding the network extension, we know that there are 29,2 customers per line kilometre, considering that there is a total transmission line extension of 1 714 km.

To determine the losses in transport and distribution lines, we used the value of 8,3% provided by Eletricidade da Madeira's report, which when applied to the consumption of 248 000 MWh/year gives us a total loss of 20 584 MWh per year.

Lastly, we analysed the overall cost of the grid. The initial investment comes from the costs regarding the installation of the T&D lines, around 38,22 M€, and from the ones regarding the installation of the voltage transformers, around 16,1 M€. The operation and maintenance costs come up to about 16,74 M€ per year. Considering these costs, a life cycle of 30 years and a discount rate of 5%, a LCOE of 0,04€/kWh or $2{,}44\times10^{-5}$ €/kWh per line km is obtained.

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