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THE TRANSMISSION LINE COST CALCULATION

Technology and Communication

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FOREWORD

This thesis has been written at Vaasan Ammattikorkeakoulu, University of Applied Sciences Degree Program in Electrical Engineering for Wärtsilä Power Plants in Vaasa, Finland.

First in all, I would like to thank Jani Aurell, Installation Costing Estimator, from Wärtsilä who gave me an opportunity to make this thesis. I would also like to thank my supervisor Olavi Mäkinen, Principal Lecturer, who helped me in difficult situations.

In addition, special thanks belong to my family for supporting and motivating me to finish this thesis.

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ABSTRACT

Author	Juho Yli-Hannuksela
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The purpose of this thesis was to develop calculation models for the WICE-ME which is used for budgeting installation costs of different size high voltage lines. The examined voltage ranges were 72.5 kV, 145 kV, 245 kV and 400 kV.

Wärtsilä provided their installation cost calculation tool, WICE-ME, as a help for this thesis. WICE-ME included the model of the installation of products provided for the customer, as well as the quotation of the materials and the cost of the installation and material.

The cost calculations were made for both installation and materials which includes all single necessary equipment such as towers, conductors and insulator strings. A chart was also created for cost calculation. This chart constituted estimated total cost of the transmission line in accordance with the power need.

As a summary of this thesis it was possible to constitute graphs for the every power model of every examined voltage rating. These graphs present the price as a function of power. From the graphs the price of the power for the known distance can be seen.

The results of this thesis have been added to the WICE-ME and these results will be used in future for the construction cost calculations of the transmission lines in power plants provided by Wärtsilä.

Keywords Selection of transmission line, cost calculation, modelling

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TIIVISTELMÄ

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Tämän opinnäytetyön tarkoituksena oli laatia laskentamallit siirtokapasiteetiltaan ja nimellisjännitteiltään erikokoisten suurjännitelinjojen asennuskustannusten laskentaan. Tutkittavina jännitealueina oli 72.5 kV, 145 kV, 245 kV ja 400 kV.

Opinnäytetyössä oli käytettävissä Wärtsilä Power Plantsin asennuskustannusten laskentaan käyttämä WICE-ME-työkalu. Työkaluun on mallinnettuna asiakkaalle tarjottavien tuotteiden asennustyö ja asennusmateriaalin määrä sekä asennustyön ja materiaalin kustannus.

Kustannuslaskenta tehtiin sekä asennus- että materiaaleille, jotka sisältävät kaikki yksittäiset komponentit, kuten pylväät, johtimet ja eristimet. Kustannuslaskentaa varten tehtiin exceliin taulukko, joka muodosti arvioidun loppusumman kyseiselle jännitealueelle tehon tarpeen mukaan.

Laskentamallien lisäksi työn lopputuloksena saatiin kullekin jännitealueen tehoalueille kuvaajat, joissa kuvaajat on kerrottu hinta- tehon funktiona. Näin ollen kuvaajista nähdään kuinka paljon tietty tehoalue tulisi maksamaan tietyllä etäisyydellä. Kuvaajista voidaan karkeasti arvioida siirtolinjan rakennuskustannus tietyllä teholla ja etäisyydellä.

Työn valmistuttua laskentamallit ohjelmoitiin WICE-ME-työkaluun ja tullaan jatkossa käyttämään siirtolinjojen rakennuskustannuslaskentaan Wärtsilän voimalaitosprojekteissa.

Avainsanat siirtolinjan valinta, kustannuslaskenta, mallintaminen

LIST OF TERMS AND ABBREVIATIONS

A	Ampere
AC	Alternative Current
DC	Direct Current
DUCK	ACSR 305-39 DUCK
EHV	Extra High Voltage
FINCH	ACSR 565/72 FINCH
HV	High Voltage
Hz	Hertz
I_N	Nominal current
kV	Kilovolt
LV	Low Voltage
mm^2	Square millimeter
MV	Medium Voltage
MVA	Mega Volt Ampere
S_N	Apparent power
UHV	Ultra High Voltage
U_N	Nominal voltage
V	Volt
VA	Volt Ampere
WICE-ME	Calculation tool of the both electrical installation contract and installation material budget for the project of the power plants.

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1. INTRODUCTION

1.1 Starting Points and Objective

The objective of this thesis was to create a model of the overhead transmission line. Components were defined for each voltage ratings which are 72.5 kV, 145 kV, 245 kV and 400 kV. Another objective was to calculate material and installation costs for the chosen components and lines.

1.2 Wärtsilä

The roots of Wärtsilä are in the village of Värtsilä, in Tohmajärvi, since year 1834. At the start Wärtsilä operated as a sawmill which was bought by Nils Ludvig Arppe in 1836. Arppe expanded the company to the Wärtsilä Rautaruukki in 1851. In 1935 Wärtsilä bought the majority of Machine and Bridge Contract Ltd, gaining also control of the Hietalahti shipyard in Helsinki and the Crichton-Vulcan shipyard in Turku. After the time of N. L. Arppe, the whole company moved to his followers. Both Wärtsilä Rautaruukki and the followers' own limited company interconnected to each other and the name was changed to Wärtsilä Aktiebolag. In 1907 name was changed for the first time to Ab Wärtsilä Oy. Wärtsilä produced their first diesel engine in 1942 which was not designed by them. The first engine designed by Wärtsilä was produced in 1960 (Wärtsilä 14). In 1987 Wärtsilä and Valmet decided to merge to one shipyard and their common name was decided to be Wärtsilä Meriteollisuus which went bankrupt in 1989. Year 1990 was really significant because of the new era begun. At that time Oy Wärtsilä Ab and Oy Lohja Ab merged and the name was decided to be Metra Oy. Metra concentrated on producing and servicing both sea engines and power plants. Metra changed its name back to Wärtsilä in 2000. /1/

Wärtsilä is a market leader in diesel and natural gas engines. The company had, at the end of 2010, 17.704 employees in 70 countries and in 160 different locations all around the world. In 2009 Wärtsilä's net sales was 5.3 billion Euros which is 13% more than last year (2010). Wärtsilä's vision is: "We will be the most valued business partner of all our customers." Wärtsilä consists of three different sections which are Ship Power, Power Plants and Services. /1/

Wärtsilä has operations in several places in Finland. The most important, and also the largest, can be found from Helsinki (headquarters), Turku (both Services, Sales, Product support, Ship Power solutions and Wärtsilä Land & Sea Academy) and also from Vaasa. The delivery centre and the R&D are both found at the centre of Vaasa. Services, Power Plants, Ship Power and also their Sales are located in Runsor, Vaasa. /1/

1.3 Power Plants

Wärtsilä Power Plants is the market leader in providing different types of power plant solutions. Wärtsilä produces three different types of power plants which are gas, oil and biofuel-fired. These power plants provide power from 1 MW up to 300 MW. Wärtsilä delivers power plants as complete turnkey projects or single equipment supplied, such as a generator. At the end of September (in 2010) 845 employers were working for Power Plants. /2/

Power Plants net sales offsets 31 % from the overall net sales in 2009. It is also notable that net sales of Power Plant have increased by 30 % from 2008 to 2009. From 2007 to 2009 it has increased almost 50 %. Also delivered megawatts (engines) have increased by 24.2 %. /2/

1.4 Cost Calculation

Wärtsilä Power Plant is using an installation costing tool called WICE-ME to estimate the mechanical and electrical installation costs of the Power Plant projects. The installation cost estimation tool is used mainly in the sales phase to budget the installation costs of the Power plant in the specific project country. Besides of the sales budgeting, the tool is also used with subcontracting when project is in the execution phase to generate the subcontracting documents and to evaluate the offers from subcontractors. /3/

The tool is build from different equipments, buildings and areas which are modelled to the tool. The models are based on the quantity of installed units. Installation units in the electrical estimation tool are cables, cable raceways, switchgears, panels and transformers which are to be installed as a part of power plant. Each unit has a specified unit price for installation work and for material. With the quantity and price of the units installation costs can be defined. /3/

The key number of the estimation is the unit price of the each unit. Most of the installation materials are delivered from Finland, but installation work is purchased locally. The tool has a global unit price database which is based on contractor inquiries and on the subcontracts of power plant projects. Depending on the country, the unit price for installation has big variations. The variation is caused by local productivity, labour hour rate and also the industrial density of the country. In Figure 1 we can notice that the ratio between Helsinki and local unit prices (in this case Argentina) is not the same for every unit because of the implementation of the installation may be different compared to Finland. /3/

Ratio between local and Helsinki prices

	Local		Local	Helsinki	Ratio
Inst. of Step-Up Transformer (100 ton)	34 775	€/pc	34 775	4 167	8,3
Inst. of Central control panel	660	€/pc	660	675	1,0
Inst. of Tank Panel	475	€/pc	475	450	1,1
Inst. of control cable, 4x1.5m on ladder, h<4m	2,15	€/m	2,15	1,66	1,3
Inst. of LV cable, 4G2.5m on ladder, h<4m	0,75	€/m	0,75	1,66	0,5
Termination (wire=d<1mm, control cable)	7,16	€/pc	7,16	2,57	2,8
MV-cable termination 240...400 mm2	57,98	€/pc	57,98	70	0,8
Inst. of horizontal ladder (w=500-1000mm, h<4m)	23,49	€/m	23,49	5,55	4,2
Inst. of Fluorescent luminaire (h<4m)	114	€/pc	114	23,45	4,9
Inst. of Disconnector	2 715	€/pc	2 715	1 125	2,4
HV Connections	341	€/pc	341	116,7	2,9
Indirect costs	32	%	32	30	1,1
Other	3		3	1	3,0
Wärtsilä	1,4		1,4	1	1,4

Figure 1. Example unit prices at WICE-ME

WICE-ME is also used to generate subcontracting document called Bill of Quantities and to evaluate the offers from potential contractors. The Bill of Quantities is an Excel based document which can be generated from the WICE-ME when the equipments, areas and buildings are inserted to the tool. The Bill of Quantities is a list of all the installation units and the quantity of each unit. The Bill of Quantities is to be send to the contractors with other inquiry documents. The contractor will use the Bill of Quantities by filling their price for each unit to the Bill of Quantities. The total offer of the contractor is automatically calculated with the estimated quantity by Wärtsilä and with the unit prices of the contractor for each unit. /3/

2. SELECTION OF TRANSMISSION LINE

2.1 Transmission Line

The objective of the electrical network is to transfer electrical power generated in power plants to the customers. High voltages are transferred at 3- phase (AC), over 110 kV and 50 Hz (60 Hz used in America) in long distances. High voltages can be transferred by both conductors and underground cables. Naturally conductor is more popular because of it is easier to repair in fault situations and because of building costs. Underground power transmission has also greater operational limitations and is used in urban areas or sensitive locations. /4/

The installation method depends on target terrain and amount of population, also country in some ways because every country has its own specified standards which are not usually allowed in other countries. Figure 2 shows typical transmission line (220 kV) with guyed portal towers. /4/

Figure 2. Transmission line with guyed portal towers

A transmission line consists of many various components. The most important are both tower and conductor which allow electricity to be transmitted from power plants to the customers. There are also some other smaller components which are necessary when electricity is transferred, such as insulators, overhead ground wire, spacers and brackets. An optical ground wire (OPGW) is needed in case if data transfer is required. All of these units have their own task to be done and mostly they are used for better safety. The selection of the transmission line includes also engineering costs, commissioning costs and civil costs. /4/

2.2 Tower

The purpose of tower is to support conductors. The tower is composed of tower body, earth wire peaks, crossarm, and both flange and diagonal. The materials of towers are used usually wood or steel. Wood is mostly used up to 110 kV at maximum (in Finland). Figure 3 shows the most used tower types which are made from wood. In Finland 110 kV is transferred with the fifth tower type in Figure 3. This tower is supported with guy wires and it is also verified as a good choice for the self-supporting towers which have a larger pole hole for the foundations. The material of the foundation is usually concrete. This increases costs to the installation. /4/

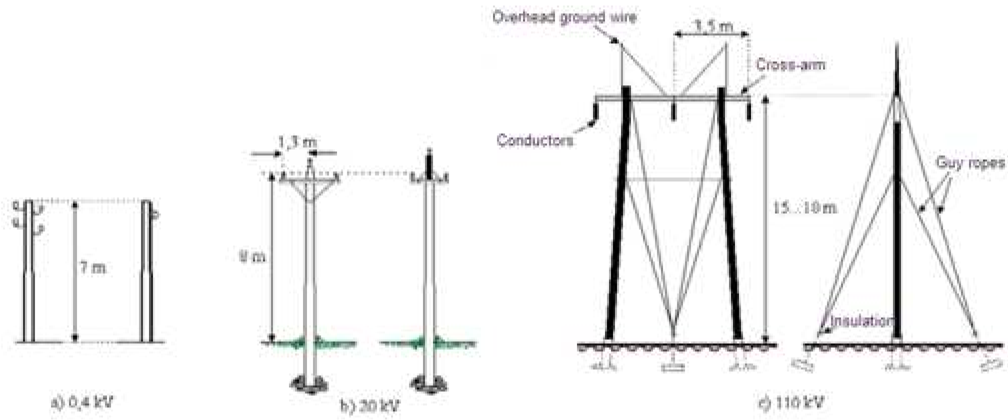

Figure 3. Wood tower structures

In Figure 3 some wood tower structures for different voltage ratings are shown. The first two pictures (a) are for low voltage which includes usually distribution to the households. 400 V is a typical voltage rating in household which is 3-phase.

The third and fourth pictures in Figure 3 are used for 20 kV and these are called the self-supporting towers. In the last picture (c) in Figure 3 are two towers for the 110 kV. The first one is a guyed portal tower which is cheaper compared to self-supporting tower because of foundation costs. The picture beside the guyed portal tower (sixth) in Figure 3 is intended also for 110 kV. /4/

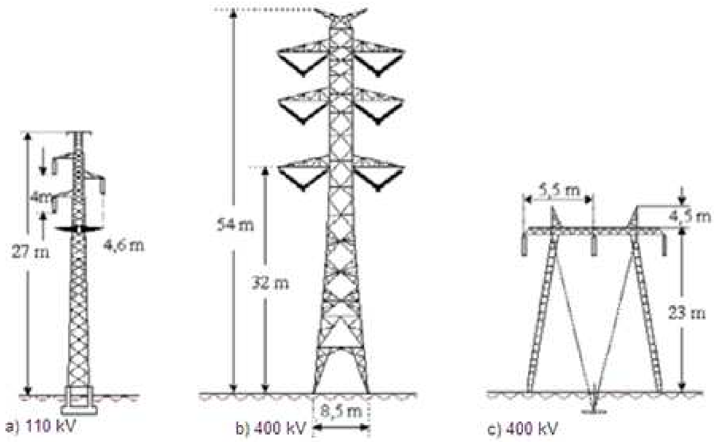

Figure 4. Steel tower structures

Steel towers are used for higher voltage lines and in situations where wood tower is not enough. This happens if more length and/or strength are required. By using steel towers, used types are tubular steel tower and different type of lattice steel towers. These are in use all over the world including Finland. But in foreign countries combined steel and concrete towers are also used. Concrete is not very often used in Finland because of its price and weight. Steel towers are shown in Figure 4. The first picture (a) is mainly intended for high voltage (~110 kV) and other two pictures in same figure (b and c) are used for extra-high voltage (~400 kV). These tower types can be also used in other voltages if necessary. Usually height and size of the tower is based on voltage and amount of circuits. /4/

The first tower in Figure 4 is called self-supporting tower which mean that this needs a larger pole hole than a guyed portal tower which is supported by guy wires. This pole hole is completely filled with concrete and the tower is recessed to the foundations. Thus, the tower leg must be deep enough underground and it can still stand during draconian outward circumstances. The tower must be embedded underground at least in the depth of 1.4 meter. This tower type has only one circuit because there are three cross-arms. Normally one arm can carry up to four conductors (1-4), which is possible with the help of spacers. In Finland up to three conductors per one phase are usually used. The spacers keep the distance between the conductors in same phase at exactly the same value as it is adjusted. The second and bigger tower is necessary if more than four conductors will be installed. There are two arms for every phase which means eight conductors at maximum (4-8). These amount of conductors are used in other World than Finland. This tower is used in situations where more power transmission is required. In these kinds of situations more conductors are usually needed. Self-supporting tower also needs approximately 45% space of the guyed portal tower demands. /4/

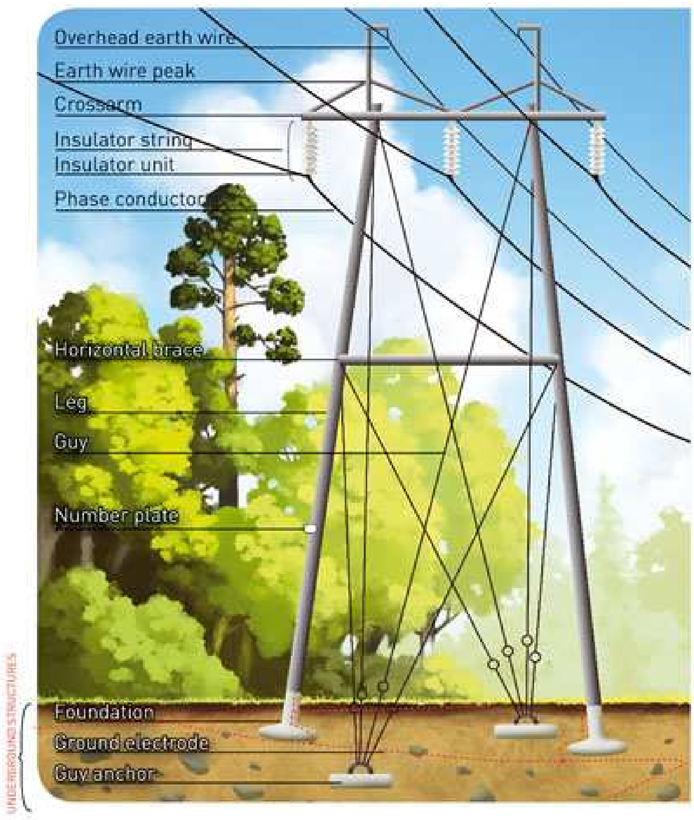

Figure 5. Main parts of the guyed portal tower

Figure 5 shows the most used tower in the transmission and in the district networks (U_R 100 kV minimum) in Finland. Reasons why the steel lattice tower is used that much in Finland is because of its weight, foundations and costs compared to the self-supporting tower. The difference between the steel lattice tower and the self-supporting tower is simple; there are not any guy wires supporting a self-supporting tower. This means a self-supporting tower needs the very large pole hole for its foundations and this hole is completely filled with concrete. Thus the concrete is the answer for the high costs as well as steel is as material because of its weight. The self-supporting tower needs much more steel into its structures than the wood towers. /4/

Though the guyed portal tower is cheaper and more lightweight, the chosen tower type was self-supporting tower for examined voltage ratings (72.5 kV, 145 kV, 245 kV and 400 kV). Reasons which led to the selection of this tower type were not only that it is used in all over Europe but it also helps Civil with land clearing. As it was earlier mentioned, this tower needs only 45 % parts of the right of way compared to the guyed portal tower. The right of way is defined in Figure 6. This leads to the conclusion that the self-supporting tower is the best option to be constructed in urban areas and thus it is a certain option. This means it is much more used in all Europe than the guyed portal tower. /4/

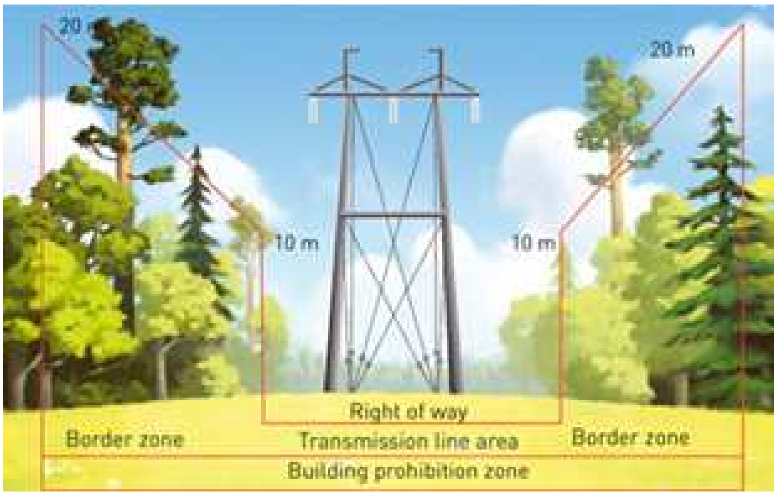

Figure 6. Building prohibition zone for guyed portal tower

By using the guyed portal tower for the 110 kV, the right of way must be from 26 to 30 meters wide. For the 220 kV the right of way is from 32 to 38 meters and for the 400 kV from 36 to 42 meters. These distances are from the homepage of Fingrid. Conductors need these specified distances to the trees, rails, buildings, etc and these can be seen from specified standards (EN 50341). /5/

Sag of span also affects the selection of the tower. There are standards which define distances from constructions and trees to the conductor. In difficult situation where the span between towers is long, towers must be higher. This ensures that conductors do not touch the ground or are not even close to the ground. It can be seen from the standards that there are specified minimal distances of the conductor to the ground (EN 50341). The height of the towers depends on voltage, number of conductors, sag and weight of the conductors. These lead to that towers are usually custom-made. The height of towers is usually customized to be increased step by step with 1.5 meter. /4/, /6/

Used tower types in each material are either suspension tower, angle suspension tower or tension tower. The suspension tower is clearly the cheapest and the most used tower type all over the world. The purpose of the suspension tower is just to sustain the conductors because there are not any affecting external forces. The weight factor for the suspension tower is one which means weight and costs of the other tower types are compared to it. If some forces are affecting, the tower type must be changed to the angle-suspension tower or to the tension tower. The angle-suspension tower is necessary in a situation where the line changes its direction. This tower is used mostly in corners. The forces of the line are so huge in the corner situations that a normal suspension tower does not fill the requirements. Angle-suspension tower is intended for this kind of situation. The factor of the weight (and costs) for the angle-suspension tower is approximately one point five. These factors mean the comparison between different types of towers. The tension tower is designed to stand in every situation which has the danger of the damaging. Neither the suspension tower nor the angle-suspension tower is enough to handle dead-end situations. This means at least two tension towers are used in every line. These towers are placed to the both end of the line. One tension tower is usually needed at intervals of three towers. Weight factor for tension tower is three. This weight factor means it is three times more expensive and heavier than suspension tower because of its steel requirements. /4/

The following factors have to be taken into account when designing towers and their foundations:

- Used loads in fastening points of the insulators, conductors and overhead ground conductors
- Wind load of the tower
- Load combination
- Ultimate limit state for each load combination
- Serviceability for each load combination (allowed deflection)
- Loads during the construction and maintenance /4/

2.3 Conductors

Many factors affect the selection of conductors. The decisive factors in the selection are economy and loading capacity of the conductor. In addition notable factors are also both mechanical demands of the installation place and also corrosion resistance. Used types are conductors and ground cables. The difference between conductor and ground cable is that the conductor is suspended over the ground by using towers, and cables are placed in the cable conduits underground. However in this case conductors are used very often in transmission of the high voltage. The materials of conductor are cobber, aluminium and aluminium alloy. In the medium voltage networks conductor is normally made from aluminium alloy or reinforced aluminium. In higher voltages the material of conductor is usually used reinforced aluminium. /4/

The loading capacity is affected by many various factors such as conductor structure, temperature of the environment, heating effect of the close position of the electrical and heating conductors, way of installation and mounting depth. /4/

Table 1. Comparison of the conductors and tower

Tower	Current conductor	Thermal transmission capacity, MVA (+30 °C)	Price, %
II hp	Ostrich	80	100
II hp	Duck	120	120
II hp	2-Duck	240	160
t	2 x Duck	240	330
t	2 x 2-Duck	480	460
II ht	3-Finch	1950	360
t	2 x 3-Finch	3900	1000

Table 1 displays the price comparison of the conductors between 110 kV and 400 kV. There is also a difference between conductors. The chosen conductors, DUCK and FINCH, have also a price difference. It depends on usually both the number of installed conductors, the material of the conductor and cross-section. But in this case selection of the tower is also very significant. From Table 1 it can be seen that a wood tower is much cheaper than any other construction material. Wood is not very often used in foreign countries which led to the selection of steel. The acronym explanations for the Table 1 are in Table 2. Specifications, technical information and also nominal currents for both conductors are shown in Appendix 1. /4/

Table 2. Explanation of the acronyms for table 4

II	=	Portal tower
hp	=	Guyed wood tower with concrete foundations
ht	=	Guyed steel tower
t	=	Self-supporting steel tower
2 x Duck	=	2 x circuits, 1 - Duck-conductor in each phase (2 conductors)
2 x 2-Duck	=	2 x circuits, 2 - Duck-conductor in each phase (4 conductors)

2.3.1 Structure of Conductor

An ACSR conductor consists of a couple of wires of steel core which is zinc coated. External skin consists of one or more layer of aluminium wires. /8/

2.4 Voltage Ratings

Voltage is the electrical potential difference between two points. Voltage is divided into three different voltage areas which are low voltage, medium voltage and high voltage (extra high voltage and ultra high voltage). Low voltages are mostly used for distribution and higher voltages for transmission. The LV area is from 0 V to 1 kV, MV from 1 kV to 45 kV and HV from 45 kV to 300 kV, EHV from 300 kV to 750 kV and UHV up to 800 kV. The examined voltage ratings are mostly used for transmission line. The range between 60-145 kV is for the regional transmission or for the large individual consumers, such as enterprises and also for medium sized power plants. 145 kV (to 300 kV maximum) is mainly for interconnecting regional areas to each other and also for transmitting medium sized power over long distances, especially in large countries like the USA and Russia. 400 kV is used for basic transmission. /4/

2.5 Power and Current Ratings

2.5.1 Apparent Power

Apparent power is used in electric power networks and also in transformers. The unit is volt-ampere (VA) and it is calculated from equation 1. This power rating is used for transformers and also for network power. Other powers are active – and reactive power. From these units the most used and the most common unit is especially active power (W) which is used in all devices: vacuum cleaners, microwave ovens, drilling machines, etc.

Only nominal current was unknown and it could have been calculated from this equation below. In Appendix 3 calculations for each voltage ratings are. Apparent power was defined to be 0-750 MVA.

$$\mathbf{I_N = \frac{S_N}{\sqrt{3} * U_N}}$$ **Equation 1**

2.5.2 Current Rating

Electrical current is movement of the electrons. Electrical current can be transmitted as alternative current (AC) and direct current (DC). Alternative current is used for instance in wall sockets and direct current is used in batteries. The difference between these is that AC changes the value and direction whereas DC remains constant.

The nominal current for ACSR 305/39 Duck is 845 ampere (80°C) and for ACSR 565/72 Finch it is 1250 ampere (80°C). But it is not recommended to use more than one ampere per one square millimeter of the aluminium (1 A / 1 mm^2). The reason for this is the power loss. If the resistance (dissipation) is getting higher the active power is increased significantly. This means that higher resistance increases power losses. The power loss can be calculated from equation 2. The cross-sections of the aluminium for the chosen conductors are shown in Appendix 1. /8/

$$\mathbf{P = I^2 * R}$$ **Equation 2**

2.6 Other Components

2.6.1 Insulators

The purpose of the insulator is to generate a safe clearance between insulating circuit and other plant. There is also one other task what insulator must do: Conductors are supported to the tower with the help of insulator. The insulator is fastened to the crossarm. /4/

The material of an insulator is porcelain or glass. Cast resin (medium voltage) and composite insulators (higher voltages) have also been used in recent years. An insulator can be a line post insulator which is used from 1.5 kV to 145 kV. In the higher voltages insulator strings are usually used. However this can also be used in the lower voltages if there is enough distance between conductors, for instance in the angle-suspension tower. A composite insulator is used in situations where there are demands of the huge mechanical strength, danger of vandalism, required light weight and dirty installation environment. /4/

The chosen insulator type is an insulator string which includes all necessary components such as cap and pin insulator and brackets. There are two different kinds of insulator string which are named V- and I-strings. /4/

2.6.2 Ground Cables

Ground cables are used in every tower. The purpose of the ground cable is to prevent the loss of the overhead ground wire, make possible function of the conductor without an overhead ground wire and also decrease ground voltage and touch voltage. The chosen ground cable is 1kV Y 1G50rm. Every tower needs 50 meter of ground cable to circumscribing the leg of the tower underground. The other end is fastened to the body of the tower. /4/

2.6.3 Spacers

The purpose of the spacers is to keep the distance between conductors exact in the same as it is adjusted. The spacers are used usually one per 50 meter which leads to 20 spacers per kilometer. /6/

2.6.4 Guy Wires

The purpose of the guy wire is to stabilize the rigidity of the tower in both directions of longitudinal and butt-end. Guy wires are used in a guyed portal tower. This means guy wires are usually used for the tower with two legs. In some ways guy wires are used also for communication towers and wind power stations which both have only one leg. When using steel lattice tower, guy wires are not necessary because of basically done foundations. /4/

2.7 Installation Costs from the Civil Point of View

2.7.1 Tower Foundation

The purpose of the foundations is to transfer the forces concentrated on towers to the ground. The foundation can be made for instance by embedding the lowest part of the tower deep enough underground or using unconnected foundation. The former is mostly used in medium voltages and the latter is used in high voltages up to 110 kV minimum. When using embedding, the wood tower must be taken underground as deep as 1/7 parts as the overall length of the tower or 1.4 meters at minimum. The tower is supported by stones from the base and ground. /4/

Special notable interactions between towers and ground are:

- Loads caused by towers
- Loads caused by stable weight of the both active earth pressure, ground and foundations

- Buoyant affecting force to the ground and foundations caused by underground water
- Unstable dislocation
- Deformation taking place in the tower or its bar
- Inclination of the tower (especially angle- and dead-end towers) /4/

2.7.2 Land Clearing

Land clearing is one of the main tasks of the Civil. Land clearing includes felling; too high trees must be cut down because of fault situations which can take place if a tree falls on the line. This means the selected tower needs a defined width of the right of way. The specified right of way for self-supporting tower is shown in Figure 7. /4/

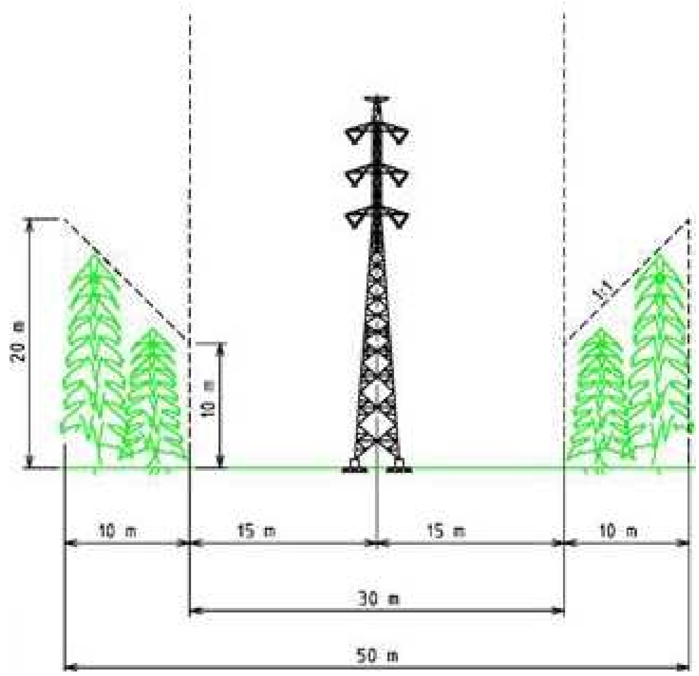

Figure 7. Right of way for self-supporting tower

Typically the guyed portal tower is better than the self-supporting tower because of the costs but the latter one needs approximately 45 % lesser right of way. When using the guyed portal tower land clearance needs more attention but the foundations do not require attention almost at all. /4/

2.8 Specification

2.8.1 Line Structure

A transmission line consists of many various components and the foremost is the tower (and conductor). The chosen tower is made from steel and is self-supporting which means no guy wires are necessary. A self-supporting tower is usually chosen for high voltage lines and mainly for urban areas because of its slight space requirement. Compared to a guyed portal tower this self-supporting tower is ten times more expensive but it helps work of the Civil with land clearing. Its foundations costs are increased because of the cost of concrete. Because of this, the chosen tower needs a large pole hole for coming up concrete foundations and also for the tower. This tower is used generally in Europe at least. With this tower at least up to 400 kV can be transmitted. /4/

2.8.2 Conductors

The second very significant factor in transmitting energy is the conductor. In this thesis, the conductor material is chosen to be (reinforced) aluminium which is taking over copper as the most used conductor material. From the selection of reinforced aluminium, the chosen conductors are ACSR 305/39 DUCK and ACSR 565/72 FINCH. In DUCK case 305 is the cross-section of aluminium and 39 is cross-section of steel. /4/, /8/

As it was mentioned earlier in chapter 2.4, 72.5 kV is used for regional transmission or for large factories and medium sized power plants. Table 3 shows the chosen conductor for each power range in 72.5 kV. These powers are concluded from Appendix 3 which shows the calculation of the nominal currents and also powers. If the number of conductors exceeds four conductors per phase, circuit have to be increased from one to two. This affects the selection of the tower. However, the weight of conductors affect also to the selection of tower. A heavier conductor causes more sag and if towers are not high enough, conductors can touch the ground. This causes many dangerous situations. /4/

The following table shows powers for 72.5 kV. From equation 1 the nominal currents for each power ratings were calculated. Power rating calculations for each voltage can be found from appendices. In the first case, where the explored conductor is ACSR 305/39 DUCK, it was calculated how much the defined conductor can resist. Nominal currents were found from the Energiakaapelit 2009 brochure. This brochure shows also some specified structural information about conductors. /4/

Table 3. Power model for 72.5 kV

Power range			Current range			Conductor	Appendix
0	-	38	0	-	305	1-DUCK	5
38		76	305		605	2-DUCK	6
76	-	114	605	-	907	3-DUCK	7
114	-	153	907	-	1218	2x2-DUCK	8
153	-	191	1218	-	1521	5-DUCK	9
153	-	229	1521	-	1823	2x3-DUCK	10
229	-	354	1823	-	2819	5-FINCH	11
354	-	425	2819	-	3384	2x3-FINCH	12
425	-	496	3384	-	3949	7-FINCH	13
496	-	567	3949	-	4515	2x4-FINCH	14

If the number of conductors exceeds four conductors per phase, the amount of circuits will be increased from one to two. This necessitates that a tower with just one circuit is not satisfactory and thus the tower have to be changed to the tower type which has two circuits. /4/

Basically DUCK was chosen to offset lower voltages, 72.5 kV and 145 kV, and FINCH just in case DUCK is not enough. These solutions are shown in Table 3 and Table 4. The power models for 145 kV are shown in Table 4. /4/

Table 4. Power model for 145 kV

Power range	Current range	Conductor	Appendix
0 - 76	0 - 305	1-DUCK	15
76 - 153	305 609	2-DUCK	16
153 - 229	609 - 911	3-DUCK	17
229 - 306	911 - 1218	2x2-DUCK	18
306 - 382	1218 - 1521	5-DUCK	19
382 - 459	1521 - 1827	2x3-DUCK	20
459 - 709	1827 2823	5-FINCH	21
709 - 750	2823 2986	2x3-FINCH	22

In Table 5 and Table 6 power models for higher voltages, 245 kV and 400 kV are shown. Finch is mainly used only for high voltage because of its cross-section. /4/

Table 5. Power model for 245 kV

Power range	Current range	Conductor	Appendix
0 - 239	0 - 563	1-FINCH	23
239 - 479	563 - 1128	2-FINCH	24
479 - 719	1128 - 1694	3-FINCH	25
719 - 750	1694 - 1767	2x2-FINCH	26

Table 6. Power model for 400 kV

Power range	Current range	Conductor	Appendix
0 - 391	0 - 564	1-FINCH	27
391 - 750	564 - 1083	2-FINCH	28

Graphs of the different costs are shown in appendixes 5-28.

3. MATERIAL COST CALCULATION

3.1 Towers

The construction material of the tower is steel. The calculations of the estimated material costs are shown in Tables 7-10. The prices of the tower depend on the cost of the steel, which is nowadays 3-3.5 €/kg, and the type of the tower. These costs of the steel are used in these tables below. The height of the tower is mentioned from the ground to the lowest cross arm. The factor for the angle-suspension tower is 1.5-2 (average 1.75). The tower price consists also of safety equipment which is approximately 10 % from the total price of the tower. More about suspension tower, angle-suspension tower and tension towers were in chapter 2.2. /4/

Table 7. Estimation mat costs for the 72.5 kV (19.5 meter height and 5230 kg)

Tower type	Price, €/pc
Suspension tower	18 305,00 €
Angle-suspension tower	32 033,75 €
Tension tower	54 915,00 €

Table 8. Estimation mat costs for the 145 kV (20.0 meter height and 5653 kg)

Tower type	Price, €/pc
Suspension tower	19 785,50 €
Angle-suspension tower	34 624,63 €
Tension tower	59 356,50 €

Table 9. Estimation mat costs for the 245 kV (20.5 meter height and 6077 kg)

Tower type	Price, €/pc
Suspension tower	21 269,50 €
Angle-suspension tower	37 221,63 €
Tension tower	63 808,50 €

Table 10. Estimation mat costs for the 400 kV (22 meter height and 6500 kg)

Tower type	Price, €/pc
Suspension tower	22 750,00 €
Angle-suspension tower	39 812,50 €
Tension tower	68 250,00 €

3.2 Conductors

The price of the conductor depends on the price of the aluminium. Table 11 shows the prices for the conductors. The ordered length of the conductor must be 4-5 % longer than the span of the towers. This is mostly because of the sag. The price of the DUCK is 3.8 €/m and price of the FINCH is 7.0 €/m.

Table 11. Material prices for conductors

Conductor	Price, €/unit
ACSR 305/39 DUCK	3 800,00 € /km
ACSR 565/72 FINCH	7 000,00 € /km
HV Connections	30,00 € /pc

3.3 Other Components

3.3.1 Overhead Ground Wire

A transmission line includes typically two earth wires, where the other can be optical ground wire (OPGW), to the top of the tower. Overhead ground wire is intended against lightning /4/

Table 12. Price for the overhead ground wire

Overhead ground wire	Price, €/unit
AACSR 106/25 SUSTRONG	1 750,00 € /km
HV Connections	30,00 € /pc

3.3.2 Optical Ground Wire (OPGW)

An optical ground wire is intended for the transmission of the communication and thus it is not necessary. An OPGW is composed of different number of fibres. One fibre is intended for a multiplexer, two pair for relay and possible one for own LAN. This leads to the number of the fibre count six at minimum. However, in Table 13 are prices for 24 and 48 fibres. /9/

Table 13. Price for the optical ground wire

OPGW	Price, €/unit	
ASLH-D(S)bb 1x24 SMF	2 950,00 €	/km
ASLH-D(S)bb 1x48 SMF	3 200,00 €	/km
Optical connection	100,00 €	/pc
Ground wire connection	30,00 €	/pc

3.3.3 Insulator Strings

The price of the insulator string is approximately 5 % from the total price of the conductor. Table 16 shows estimated prices for the different insulator string types.

Table 14. Material prices for the insulator strings

Voltage	Insulator string	Number of caps (pcs)	Insulator length (m)	Price, €/pc
72,5 kV	I-string	5	1	160,00 €
	V-string	10	1	305,00 €
145 kV	I-string	8	2	280,00 €
	V-string	16	2	470,00 €
245 kV	I-string	12	2	345,00 €
	V-string	24	2	650,00 €
400 kV	I-string	20	4	600,00 €
	V-string	40	4	1 000,00 €

3.3.4 Ground Cable

The cross-section of the ground cable is less than the cross-section of the conductor. This leads to the decreased installation costs but not material costs. The material cost of the ground cable is 3.4 €/m. Though the cost of the cable is so much, transmission line does not require it as much. Every tower needs 50 meters of ground cable which is used to surround legs of the tower underground. Basic tower groundings are composed of foundations, J-loops, guy wires and copper rope which splices legs of the tower. Prices for the ground cable are shown in Table 15. /3/

Table 15. Price for the ground cable

Ground cable type	Price, €/unit	
1kV Y 1G50rm	3 400,00 €	/km
Earthing connections	0,90 €	/pc

3.3.5 Spacer

Spacers are required for every phase in distance of 50 meters if there are two or more installed conductors in same phase. In some ways, spacers between phases are also used. One piece costs 30 €. The material price for the spacer is shown in Table 16.

Table 16. Material prices for the spacers

Spacer	Quantity	Price, €
50m	1 pc	30 €

4. INSTALLATION COST CALCULATION

4.1 Towers

The installation of the tower depends on terrain and tower type. The installation costs are usually approximately 15-30 % of the total costs. Installation cost of the tower is 0.5 €/kg. Tables 17-20 show the estimation installation costs of the towers for the different voltages. As it was earlier mentioned, the angle-suspension tower is 1.5-2 times heavier than the suspension tower and the tension tower is three times heavier than the suspension tower. These affect also the costs of the installation with the same coefficients. /7/

Table 17. Estimation inst costs for the 72.5 kV (19.5 meter height and 5230 kg)

Tower type	Price, €/pc
Suspension tower	2 615,00 €
Angle-suspension tower	4 576,25 €
Tension tower	7 845,00 €

Table 18. Estimation inst costs for the 145 kV (20.0 meter height and 5653 kg)

Tower type	Price, €/pc
Suspension tower	2 615,00 €
Angle-suspension tower	4 576,25 €
Tension tower	7 845,00 €

Table 19. Estimation inst costs for the 245 kV (20.5 meter height and 6077 kg)

Tower type	Price, €/pc
Suspension tower	3 038,50 €
Angle-suspension tower	5 317,38 €
Tension tower	9 115,50 €

Table 20. Estimation inst costs for the 400 kV (22 meter height and 6500 kg)

Tower type	Price, €/pc
Suspension tower	3 250,00 €
Angle-suspension tower	5 687,50 €
Tension tower	9 750,00 €

4.2 Conductors

Wärtsilä has its own price for the installation of the conductors. The price depends on diameter of the conductor. The installation of the one meter costs 1.72 €/m with DUCK and 2.42 €/m with FINCH. The estimation of the installation costs for the conductors are shown in Table 21.

Table 21. Installation costs of the conductors

Conductor	Price, €/unit	
ACSR 305/39 DUCK	1 720,00 €	/km
ACSR 565/72 FINCH	2 420,00 €	/km
HV connections	70,00 €	/pc

4.3 Other Components

4.3.1 Overhead Ground Wire

Normal overhead ground wire costs are shown in Table 22. The installation costs of the overhead ground wire were taken from the Wärtsilä database. The installation of the overhead ground wire costs 1.17 €/m plus connections.

Table 22. Installation costs of the overhead ground wire

Overhead ground wire	Price, €/unit	
AACSR 106/25 Sustrong	1 170,00 €	/km
Ground wire connection	30,00 €	/pc

4.3.2 Optical Ground Wire

The installation costs of the OPGW and its connection costs are shown in Table 23. The installation costs of the optical ground wire compared to the normal overhead ground wire are a little bit higher because of the amount of fibres in the optical ground wire. These fibres need to be connected to each other very carefully. The installation of the OPGW costs 1.72 €/m plus connections.

Table 23. Installation costs of the optical ground wire

Optical Ground Wire	Price, €/unit	
ASLH-D(S)bb 1x24 SMF	1 720,00 €	/km
Optical connection	200,00 €	/pc
Ground wire connection	30,00 €	/pc

4.3.3 Insulator Strings

Table 24 shows the estimated prices of the installation for the insulator strings. The prices are assumed to be 78 % from the material costs of the insulator strings. This percentage was taken from the database of the Wärtsilä's Switchyard.

Table 24. Installation costs of the insulator strings

Voltage	Insulator String	Number of caps (pcs)	Insulator length (m)	Price, €/pc
72,5 kV	I-string	5	1	124,80 €
	V-string	10	1	237,90 €
145 kV	I-string	8	2	218,40 €
	V-string	16	2	366,60 €
245 kV	I-string	12	2	269,10 €
	V-string	24	2	507,00 €
400 kV	I-string	20	4	468,00 €
	V-string	40	4	780,00 €

4.3.4 Ground Cable

Table 25 shows installation prices for the ground cable. Needed length of the one kilometer is 150 meters because of three towers. This value comes from the calculations where number of towers is three and needed length of the ground cable per one tower is 50 meters.

Table 25. Installation costs of the ground cable

Product	Price, €/unit	
Ground cable	1 200,00	/km
Earthing connections	2,90	/pc

4.3.5 Spacer

The installation prices for the spacer are shown in Table 26. These prices were taken from the installation database of the Wärtsilä's Switchyard.

Table 26. Installation costs of the spacers

Product	Price, €/pc
Spacer	10,00 €

5. OTHER COSTS

5.1 Civil Costs

Civil costs consist of land clearing and foundations. The unconnected foundation is mostly constructed from the reinforced concrete. The costs of the concrete are shown in Table 27. The table shows also work included in the foundations. The total cost of the foundations is 194 €/m^3 without an iron fitting. According to information from the Civil Cost Estimator in Wärtsilä the pole hole is approximately 50 m^3 for the one tower. Size of the pole hole also depends on the size of the tower. If the size of the foundation is 50 m^3 with 4000 kg of iron fitting the total cost of the foundations is 17240 €. This cost is for suspension tower. In cost calculations the size of the pole hole 45-65 m^3 is used. /4/ /10/

Table 27. Foundation costs

Earth excavation	4	€/m^3
Earth filling	16	€/m^3
Boxing work	42	€/m^3
Concrete	130	€/m^3
Iron fitting	1,91	€/kg

Land clearing costs are shown in Table 28. The land clearing of the one kilometer cost approximately 31000 € if the width of the right of way is 30 meter. This is calculated by assuming the costs of the land clearing to 1.03 €/m^2.

Table 28. Land clearing costs

Amount of trees	**Price, €/m^2**
Treeless	0,60 €
Little amount of trees	0,80 €
Dense forest	1,70 €

5.2 Engineering Costs

The engineering cost is 10 % of the total costs according to experience of Eltel Networks. The engineering is always necessary when designing conduction routes but special observation is needed in situations where the terrain is uneven. In this kind of situation the tower might need to be different, the span might be greater or weather might be different. This might cause different amount of loads, such as freeze, snow, wind or avalanche. /7/

5.3 Commissioning Costs

The commissioning costs are approximately one percent of the total cost of the transmission line. The commissioning costs include the final inspection which is done by walking throw the line. The transmission line does not have any units which need to be tested, such as motors. /7/

6. CONCLUSIONS

The purpose of the thesis was to model components, material costs and installation costs for the high voltage transmission line. The power models were already mentioned in chapter 2.8 and cost calculation details in chapters 3 and 4. Some specifications of the components, graphs of the cost calculations and also current/power calculations are shown in the appendices.

Figure 8 shows the percentages of the parts which are included in the total cost. From this figure it can be seen that Civil costs, installation costs and material costs are three the most expensive parts in total costs.

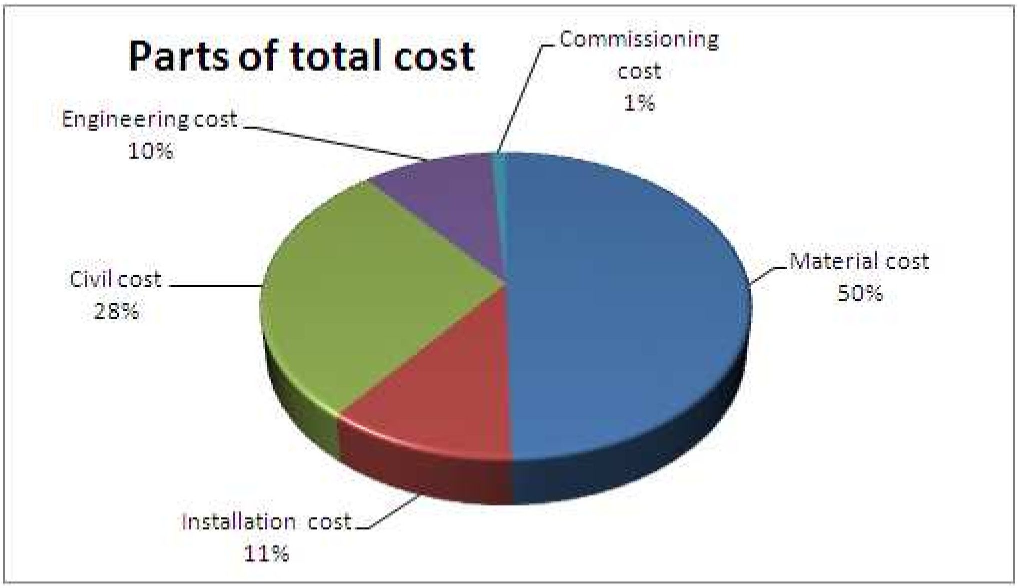

Figure 8. Estimated parts of the total cost for 8 km (72.5 kV)

The estimate cost calculations for the line has been also created for this thesis. These calculations contain different tower types, conductors, overhead ground wire, optical ground wire, ground wire and other smaller components, such as insulator strings and spacers. These calculations are completely automatic and it calculates necessary components, required length and thus also material costs and installation costs. The example calculations are shown in Appendix 4.

The reason for the higher costs of the first kilometre in every graph in appendixes 5-28 is that every line needs at least two tension towers. Normally every third tower is the tension tower. This leads to the increased costs because those tower types costs three times more than normal suspension towers and two times more compared to angle-suspension towers. When the line is longer, especially over 4 kilometres, the percent part of the suspension towers is increased and this leads to the lower costs per kilometre.

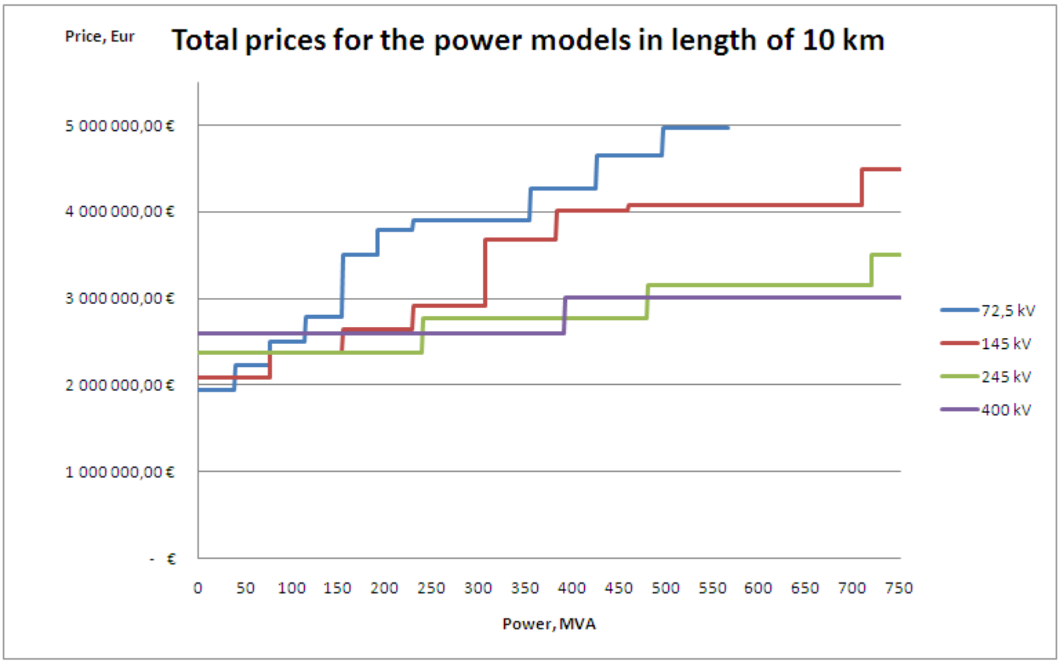

Figure 9. Prices of the voltage models for the 1 kilometer

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Appendix 1. Chosen conductor specification

Electrical properties

Product name		ACSR 305/39 DUCK	ACSR 565/72 FINCH
IEC		305-A1/S1A-54/7	565-A1/S1A-54/19
EN		305-AL1/39-ST1A	565-AL1/72-ST1A
Electrical number		01 202 21	01 202 24
STRUCTURE INFORMATION			
Aluminium			
Number of wires		54	54
Diameter of wires /	mm	2,68	3,65
Cross-section /	mm^2	305	565
Mass /	kg/km	842	1562
Steel			
Number of wires		7	19
Diameter of wires /	mm	2,68	2,19
Cross-section /	mm^2	39,5	71,6
Mass /	kg/km	309	561
Conductor			
Number of wires		61	73
Diameter of wires /	mm	24,1	32,9
Cross-section /	mm^2	344	637
Mass /	kg/km	1151	2123
DELIVERY INFORMATION			
Standard delivery length /	m	2500	1400
Delivery coil		K22	K22
Mass cable+coil	kg	3290	3380
MECHANICAL INFORMATION			
Cable nominal breaking strength	kN	96,8	174
Conductor start elasticity module	N/mm^2	50000	46000
Conductor end elasticity module	N/mm^2	67000	63000
Conductor heat elongation factor	1/K	$19{,}3 \times 10^{-6}$	$19{,}3 \times 10^{-6}$
ELECTRICAL INFORMATION			
Conductor nominal direct current resistance conductor (20 °C)	ohm/km	0,0949	0,0512
LOADING CAPACITY			
In the air conductor 80 °C	A	845	1250
THERMAL SHORT CIRCUIT CAPACITY			
Maximum 1 sec short circuit current	kA	32,5	60,1

Appendix 2. Example of the insulator string, 6 pcs, and its price (€)

INSULATOR STRINGS, 6 PCS
DUL-134205 U120BS

Product	Insulator string, 6 pcs
Type	DUL-134205 U120BS
Capacity	64,607
Weight	29,35

Price, vat 0 %	194,00 / 1 pcs
Price, vat 23 %	236,68 / 1 pcs

Appendix 3. Nominal current calculations

72,5	kV	SN, MVA	IN, A	DUCK	FINCH	Tower type
		38	305,00	1		1 circuit
		76	605,22	2		1 circuit
		114	907,83	3		1 circuit
		153	1218,41	4		1 circuit
		191	1521,02	5		2 circuit
		229	1823,63	6		2 circuit
		354	2819,06		5	2 circuit
		425	3384,47		6	2 circuit
		496	3949,87		7	2 circuit
		567	4515,28		8	2 circuit
145	**kV**	**SN, MVA**	**IN, A**	**DUCK**	**FINCH**	**Tower type**
		76	305,00	1		1 circuit
		153	609,20	2		1 circuit
		229	911,82	3		1 circuit
		306	1218,41	4		1 circuit
		382	1521,02	5		2 circuit
		459	1827,61	6		2 circuit
		709	2823,04		5	2 circuit
		750	2986,29		6	2 circuit
245	**kV**	**SN, MVA**	**IN, A**		**FINCH**	**Tower type**
		239	563,21		1	1 circuit
		479	1128,78		2	1 circuit
		719	1694,35		3	2 circuit
		750	1767,40		4	2 circuit
400	**kV**	**SN, MVA**	**IN, A**		**FINCH**	**Tower type**
		391	564,36		1	1 circuit
		750	1082,53		2	1 circuit

Appendix 4. Estimated calculations for the 145 kV (76-153 MVA, 15 km)

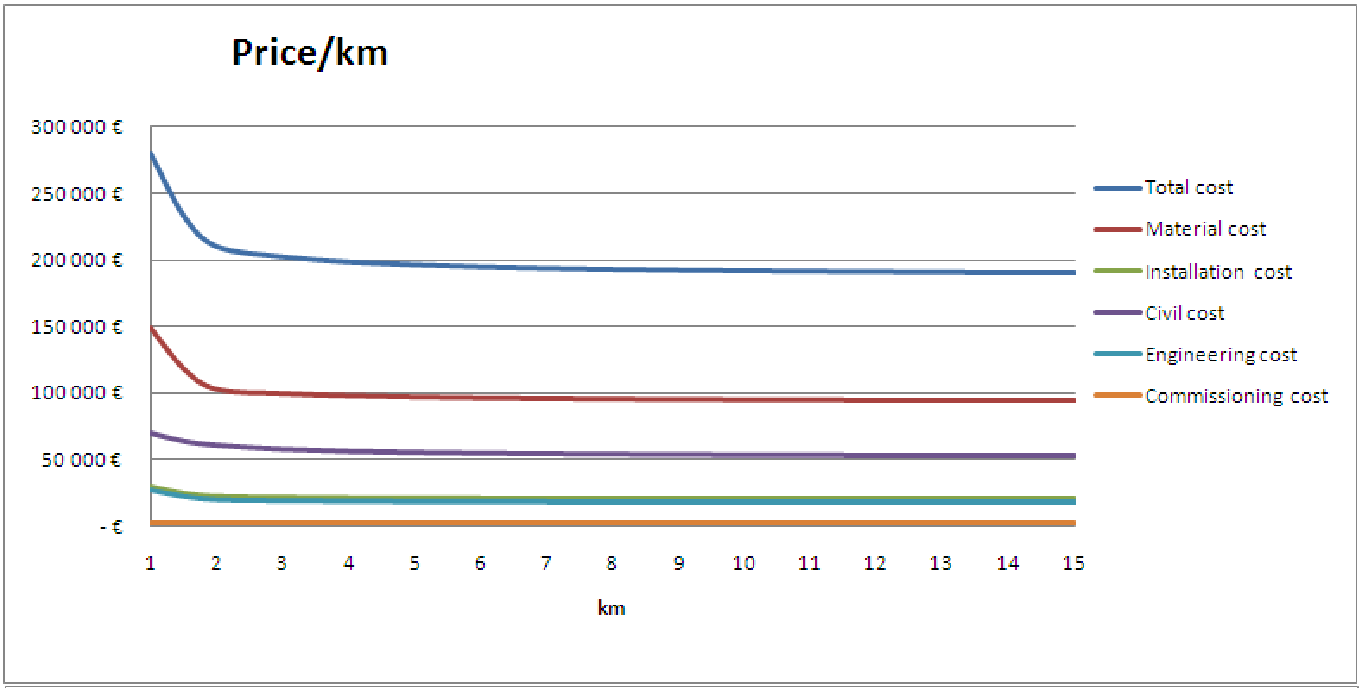
Voltage selection: 145 kV

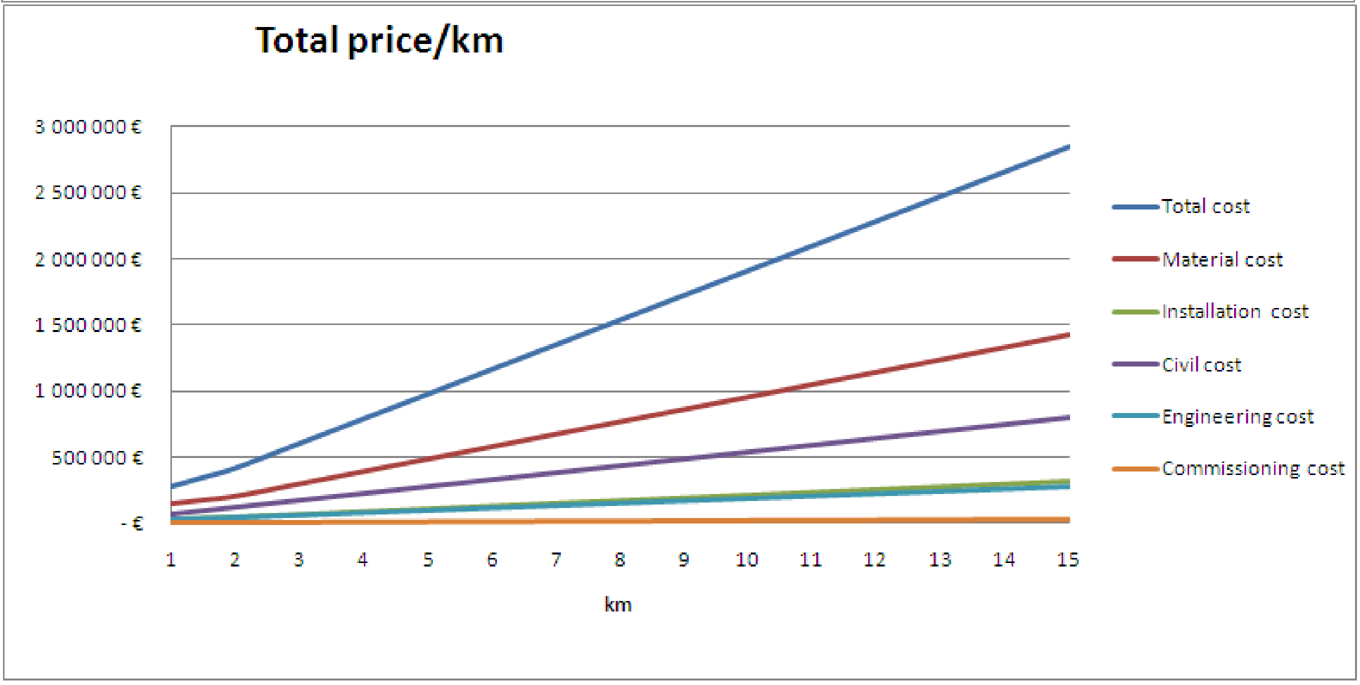
Power selection: 2D. 76-153 MVA

		Value	
Amount of circuits	0	1	
Distance, km	15	15	
Amount of DUCK conductors per phase	0	2	
Amount of FINCH conductors per phase	0	0	
Amount of insulator strings, I-type	0	93	
Amount of insulator strings, V-type	0	0	
Total power loss with maximum capacity		66 211	W
Power loss per 1 km with maximum capacity		4 414	W

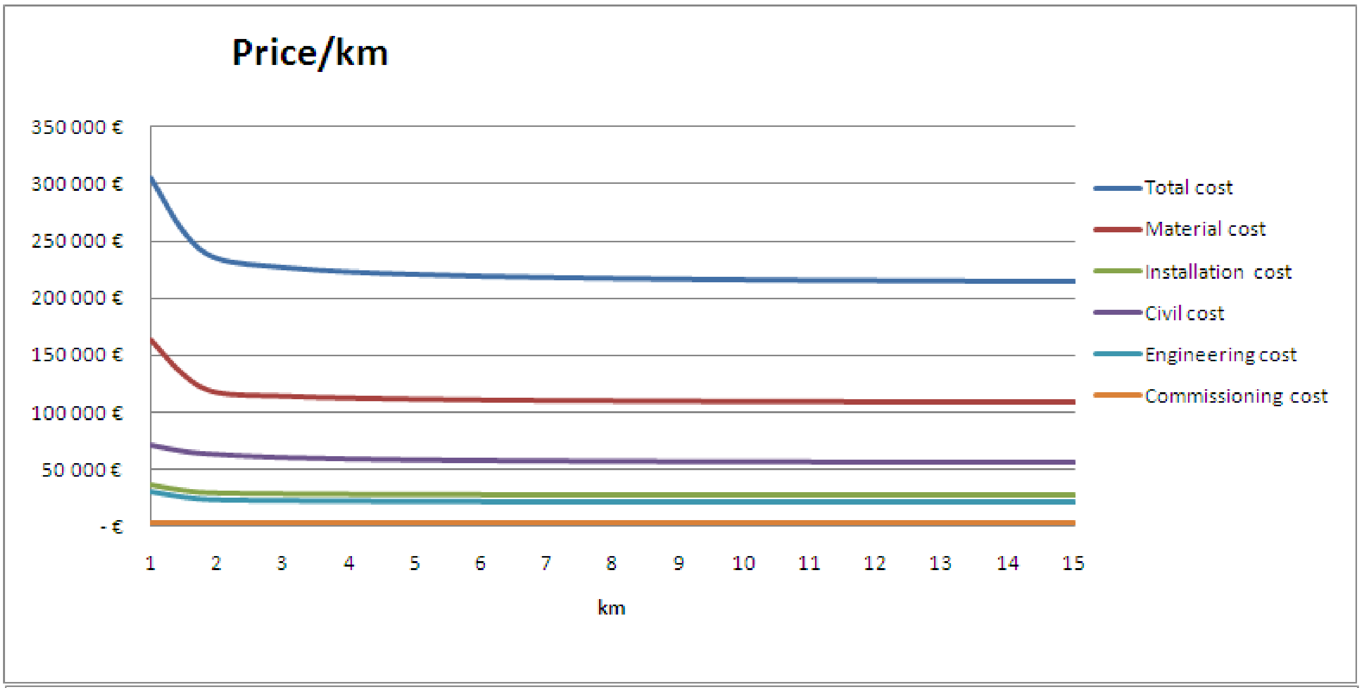
Material / Item name	Unit	Total Quantity	Material cost / unit	Total Material Cost	Installation (work) cost /	Total Installation Cost	Total costs	Remarks
Steel lattice tower	pcs	31					1 379 332,00 €	Span = 500 m
Suspension tower	pcs	16	19 785,50	316 568,00	2 826,50	45 224,00		
Angle-suspension tower	pcs	0	34 624,63	-	4 946,38	-		
Angle-strain tower	pcs	15	59 356,50	890 347,50	8 479,50	127 192,50		Two pieces at minimum
ACSR 305/39 DUCK	km	94,5	3 800,00	359 100,00	1 720,00	162 540,00	521 640,00 €	1 conductors per phase, +5%
ACSR 565/72 FINCH	km	0	7 000,00	-	2 420,00	-	- €	1 conductors per phase, +5%
HV connections	pcs	102	30,00	3 060,00	70,00	7 140,00	10 200,00 €	Delivery length 2400 m
AACSR 106/25 Sustrong	km	15,75	1 750,00	27 562,50	1 171,00	18 443,25	46 005,75 €	1 conductors per line, +5%
Ground wire connection	pcs	17	30,00	510,00	30,00	510,00	1 020,00 €	Delivery length 2500 m
ASLH-D(S)bb 1x24 SMF	km	15,75	2 950,00	46 462,50	1 720,00	27 090,00	73 552,50 €	1 conductors per line, +5%
Optical connection	pcs	10	100,00	950,00	200,00	1 900,00	2 850,00 €	Delivery length 4000 m
Ground wire connection	pcs	10	30,00	285,00	30,00	285,00	570,00 €	
Ground cable	pcs	1,55	3 400,00	5 270,00	1 200,00	1 860,00	7 130,00 €	Length 50 m per tower
Earthing connections	pcs	62	0,90	55,80	2,90	179,80	235,60 €	2 per ground cable
Spacer	pcs	900	30,00	27 000,00	10,00	9 000,00	36 000,00 €	20 per span
Insulator string, I	pcs	93	280,00	26 040,00	218,40	20 311,20	46 351,20 €	~5 % from the price of the overhead line
Insulator string, V	pcs	0	470,00	-	366,60	-	- €	2 x 5 % from the price of the overhead line
				Total material costs 1 703 211,30 €		Total installation costs 421 675,75 €	Total costs (mat + inst) 2 124 887,05 €	
				Foundations		Land clearing	525 527,50 €	
Civil				525 527,50 €		- €		
Engineering	%	10					294 461,06 €	10% from the total price
Commissioning	%	1					29 446,11 €	1% from the total price
						Total	2 974 321,71 €	
						Price per 1 km	198 288,11 €	

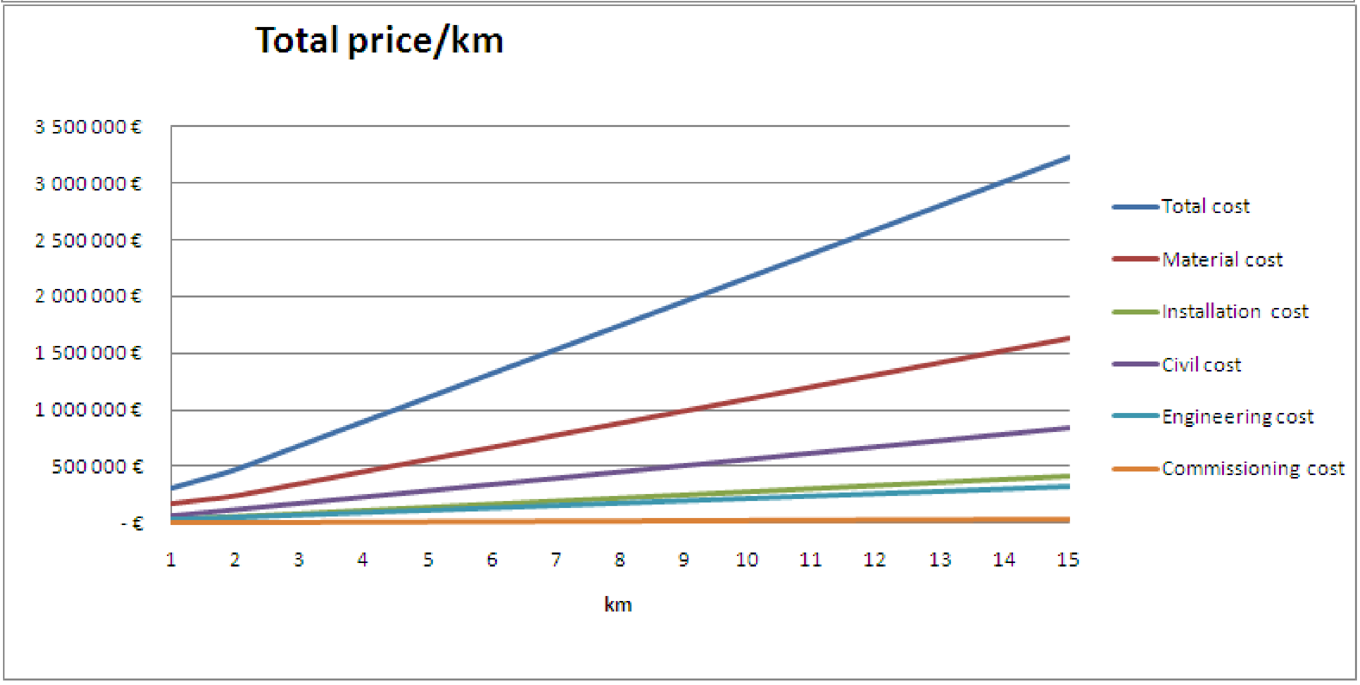
Appendix 5. 72.5 kV: 0-38 MVA, 1-Duck



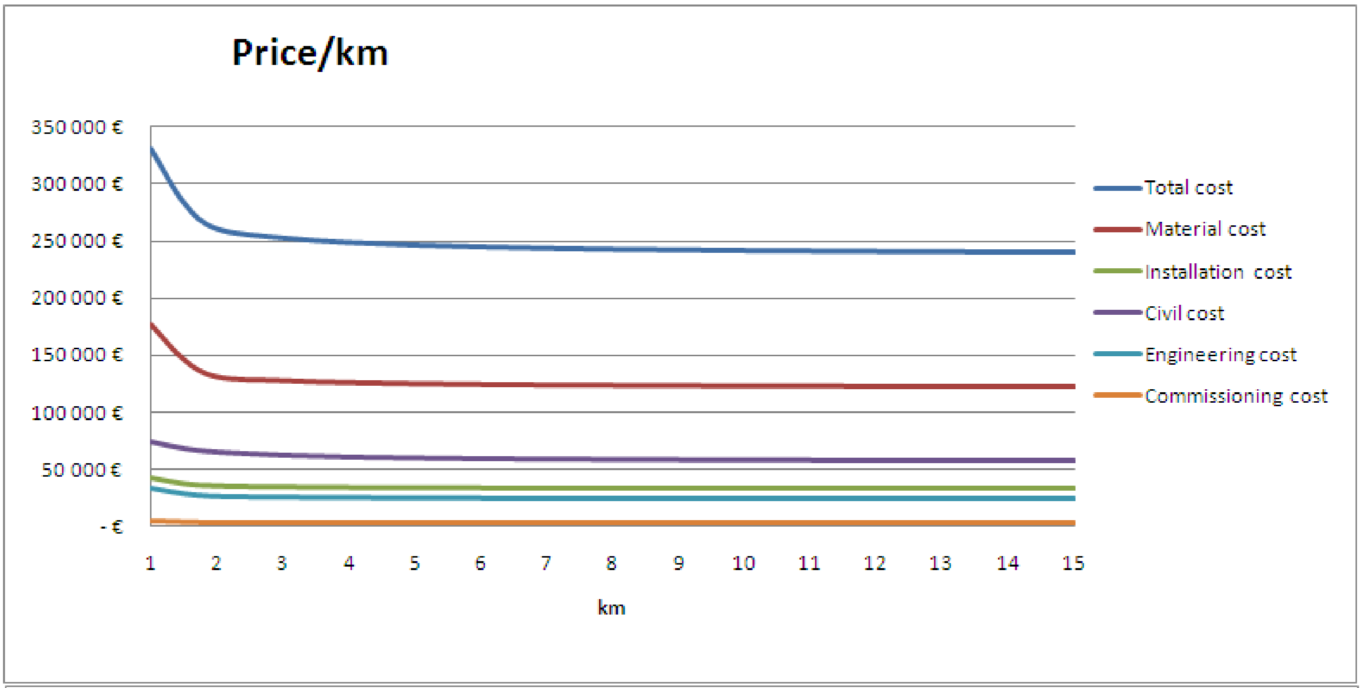


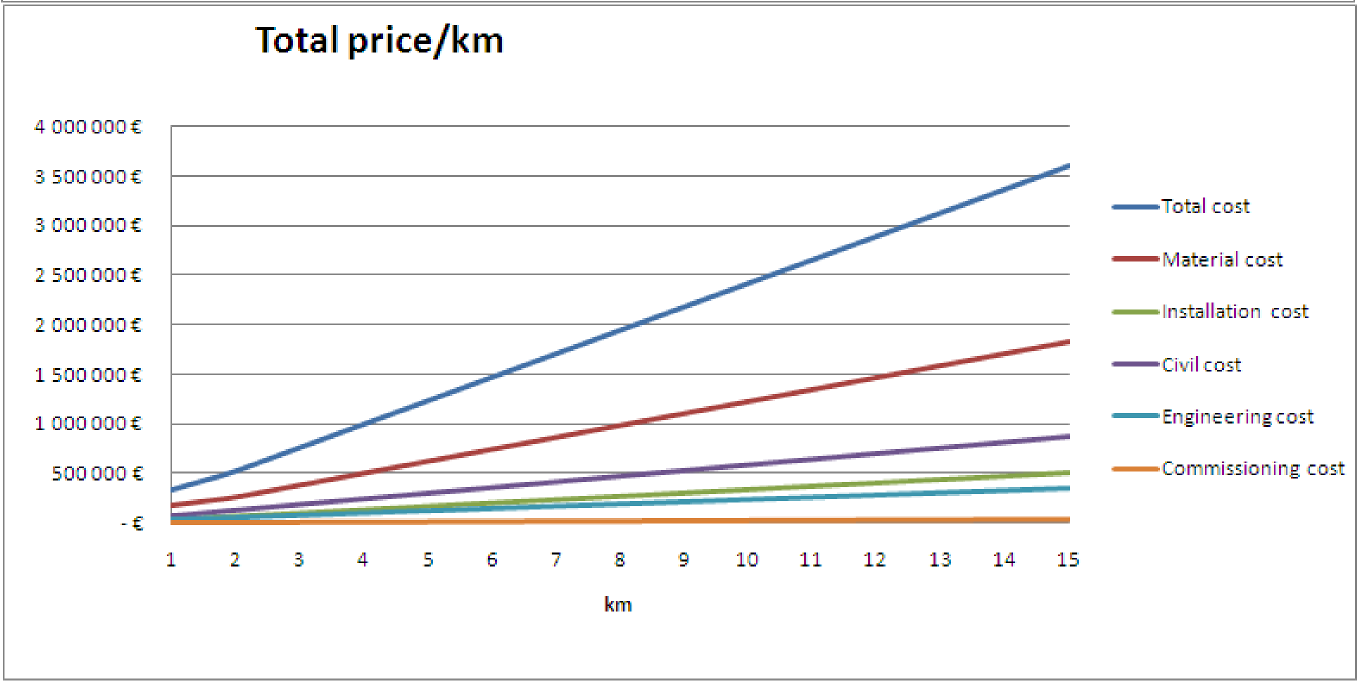
Appendix 6. 72.5 kV: 38-76 MVA, 2-Duck



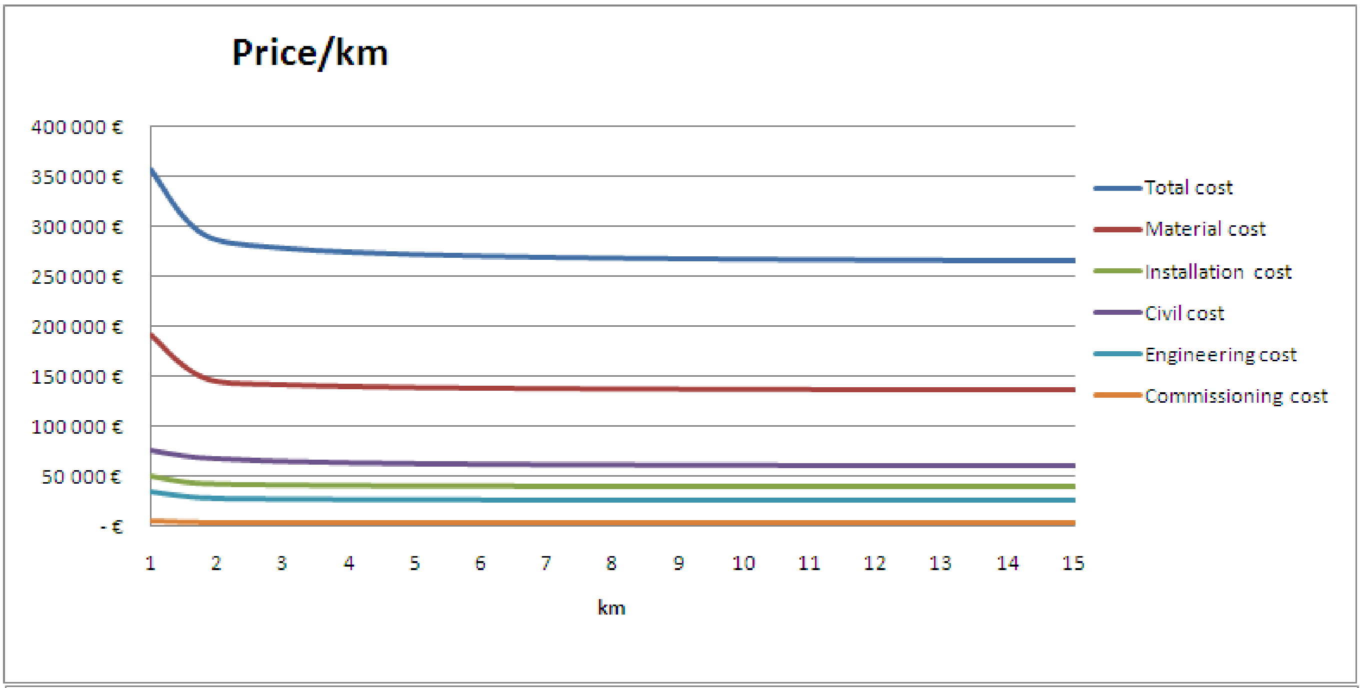


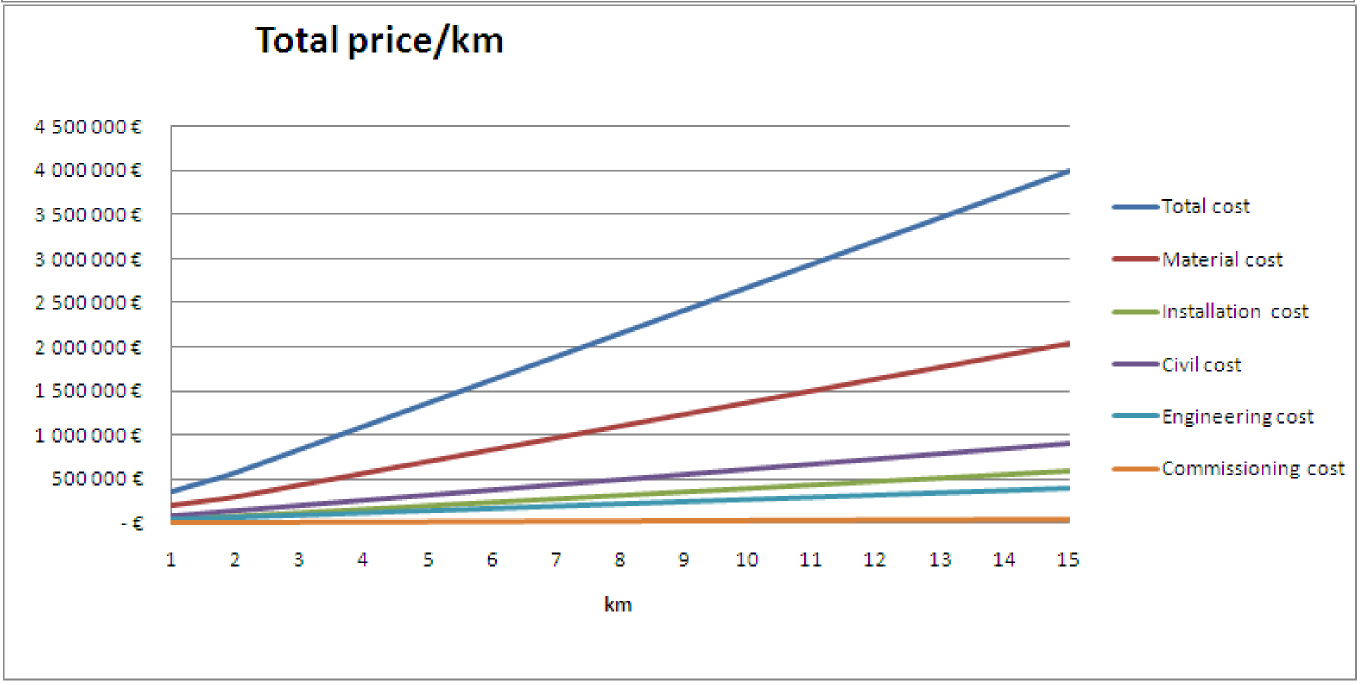
Appendix 7. 72.5 kV: 76-114 MVA, 3-Duck



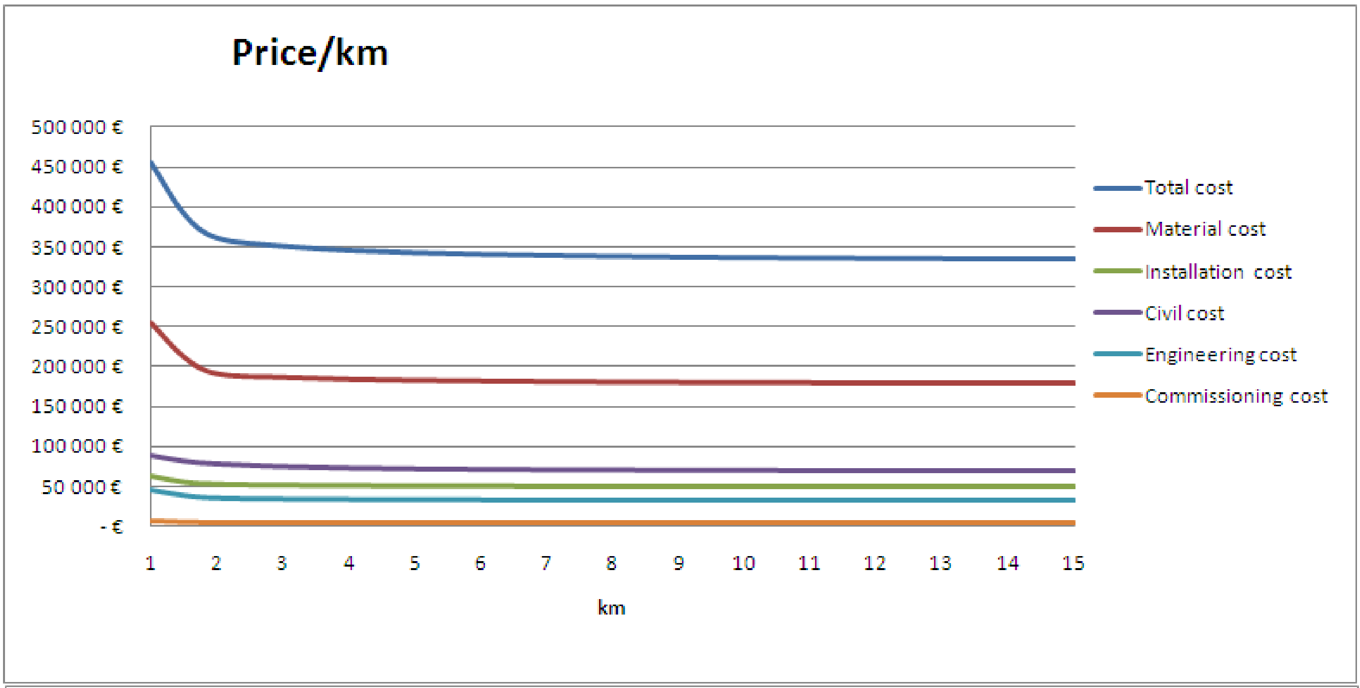


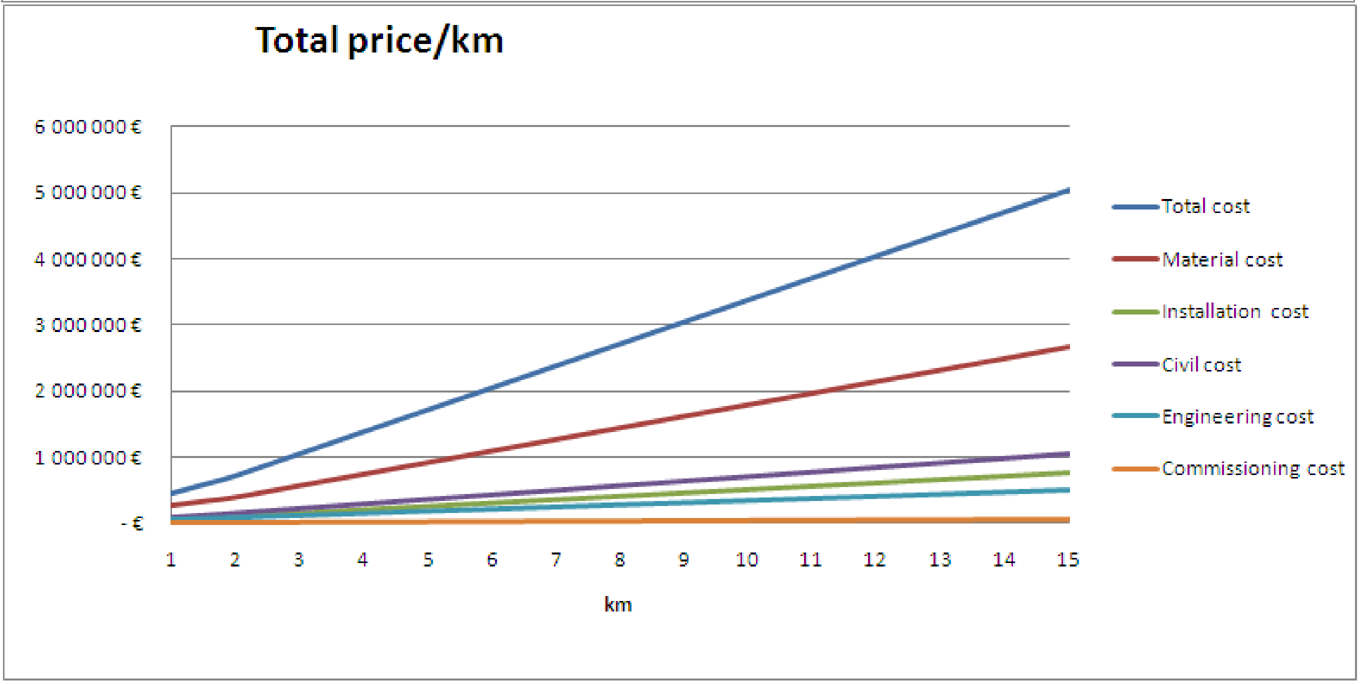
Appendix 8. 72.5 kV: 114-153 MVA, 4-Duck



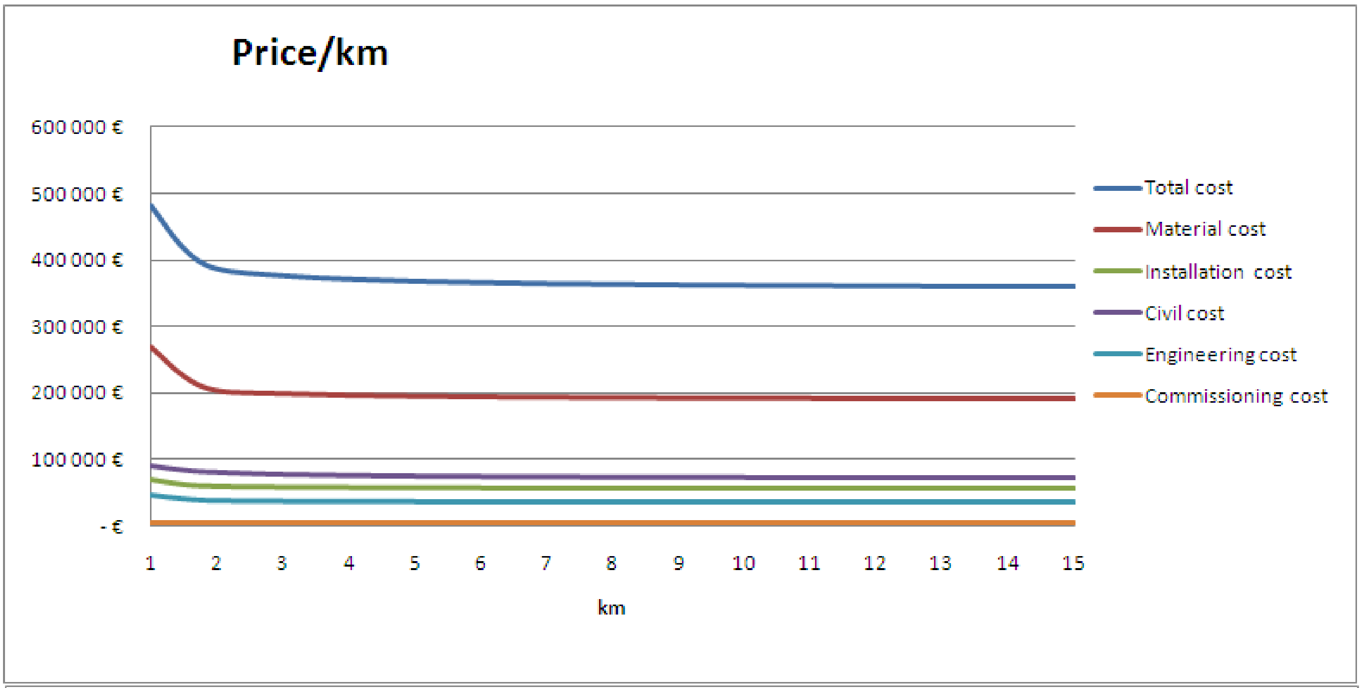


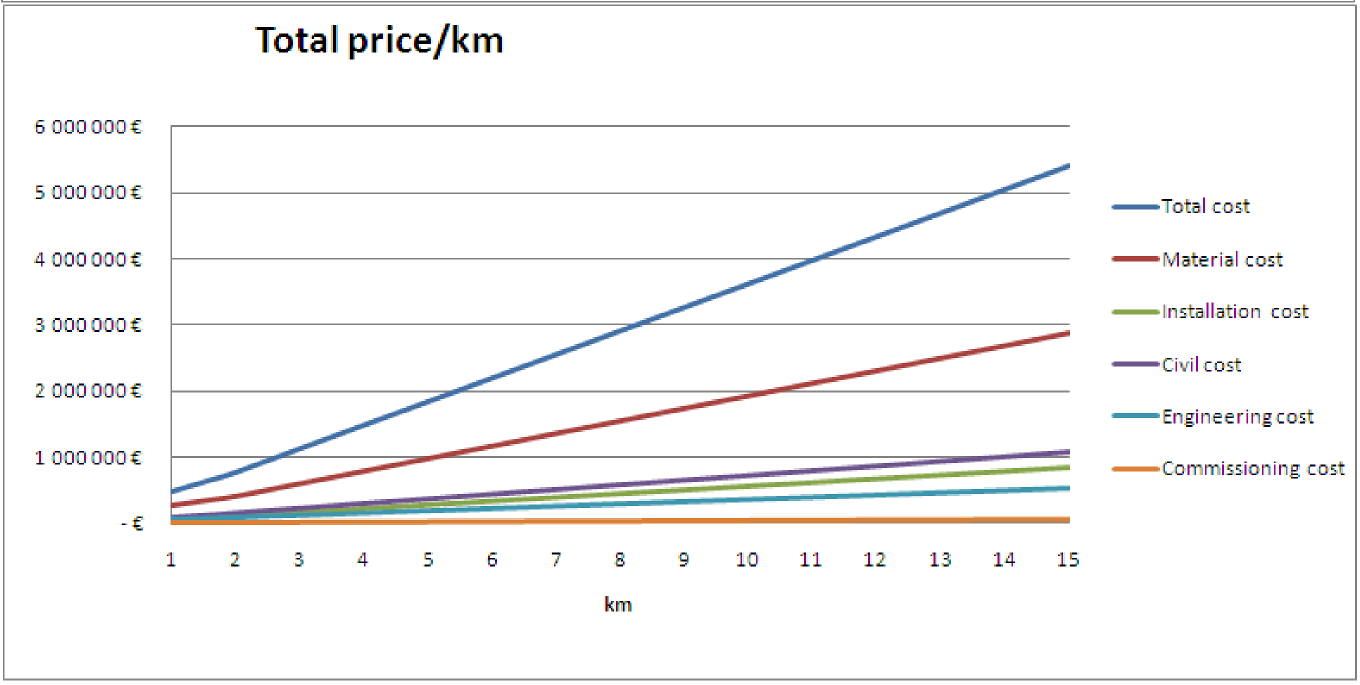
Appendix 9. 72.5 kV: 153-191 MVA, 5-Duck



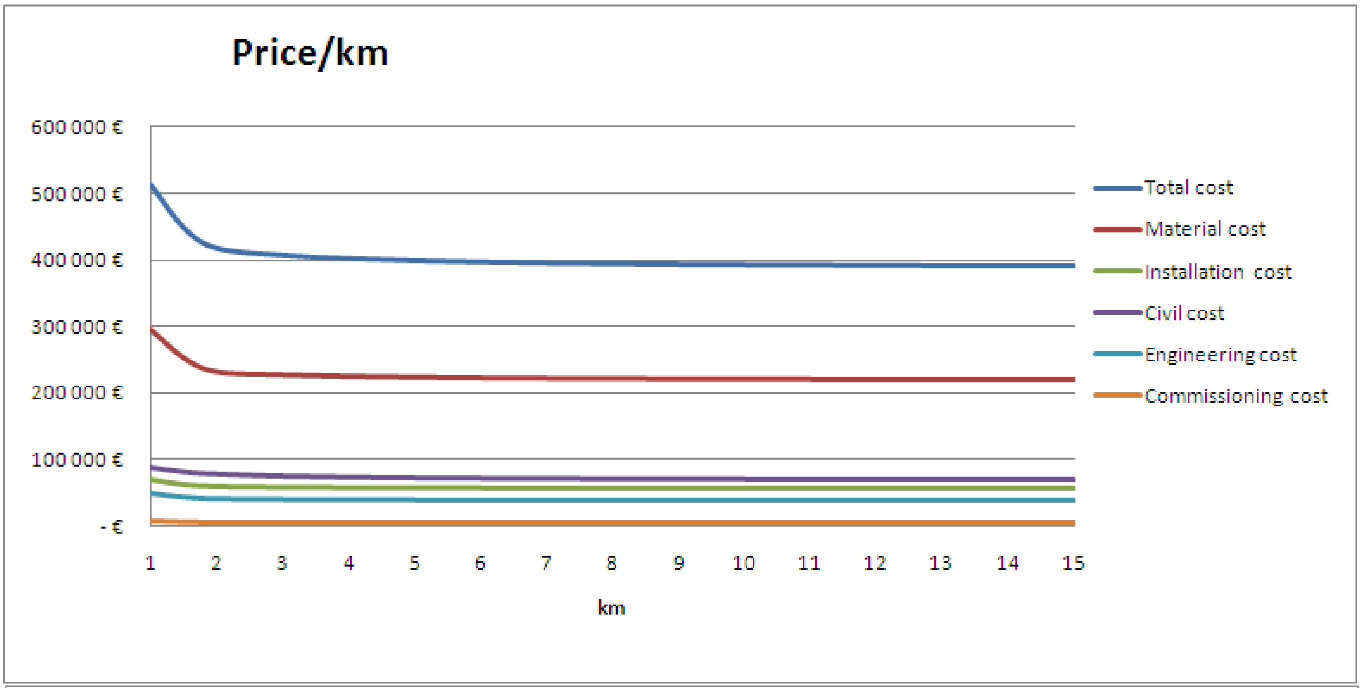


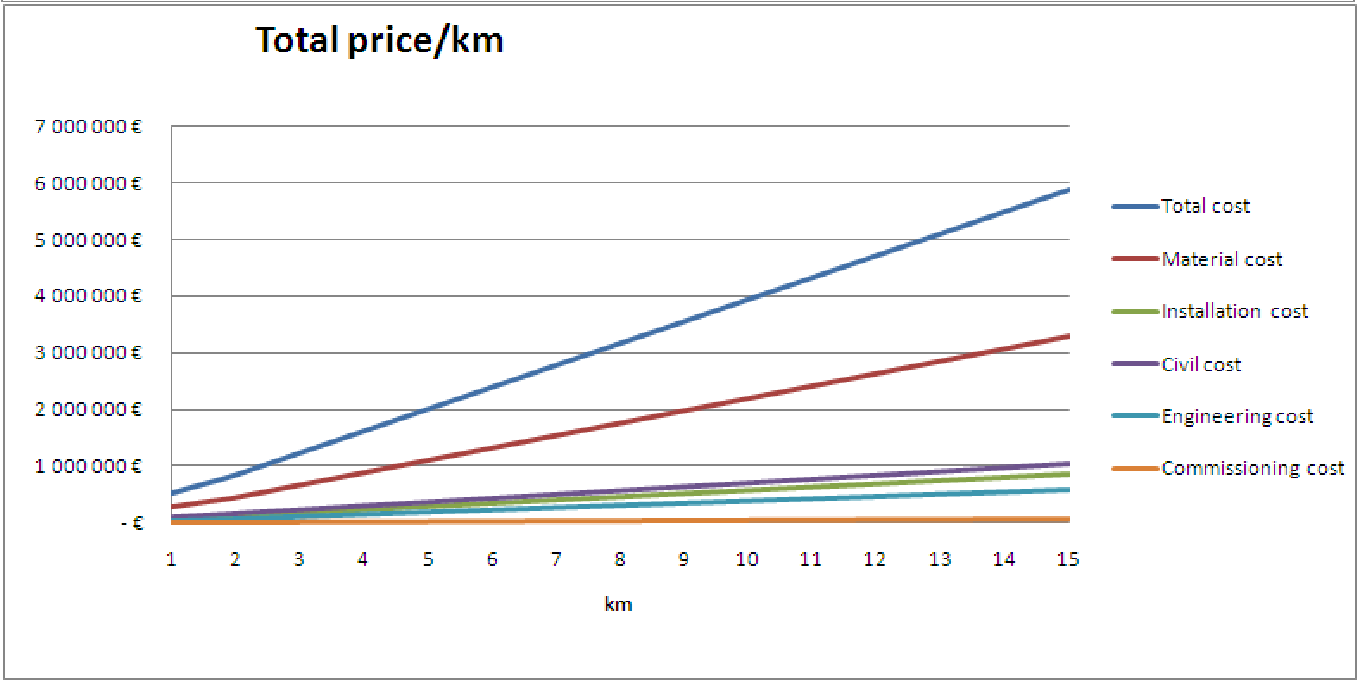
Appendix 10. 72.5 kV: 191-229 MVA, 6-Duck



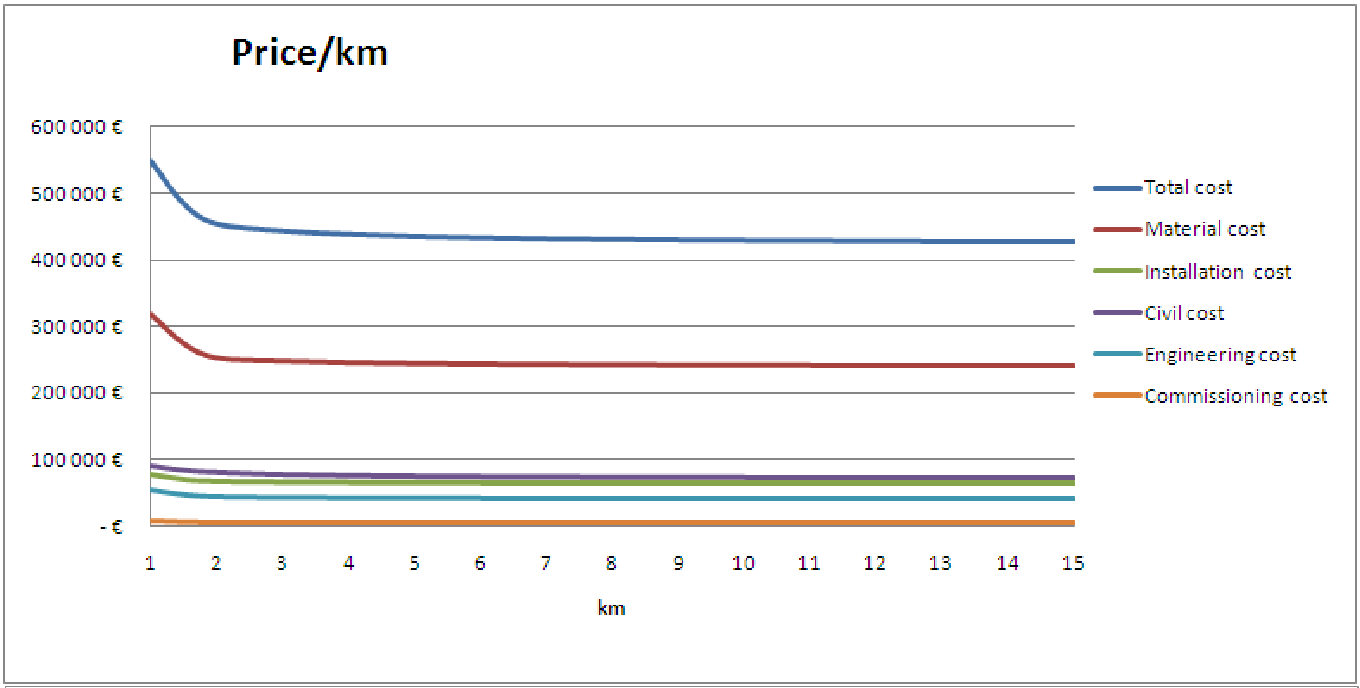


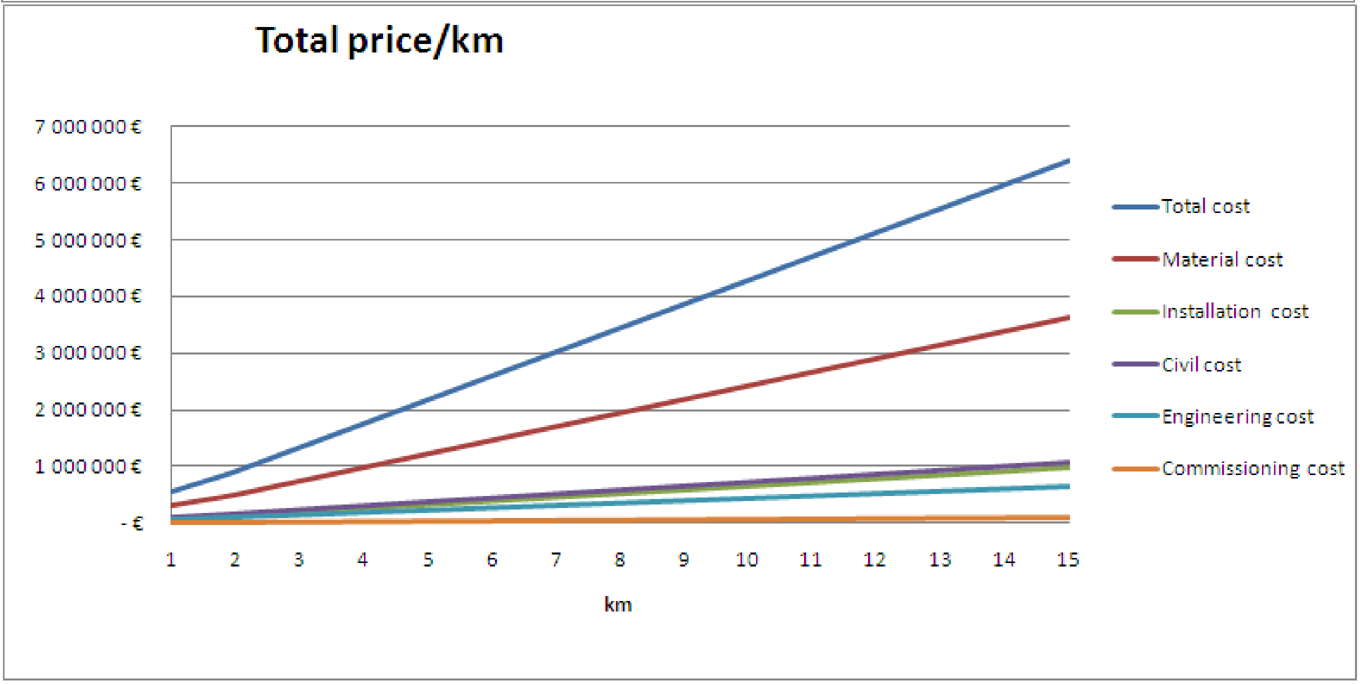
Appendix 11. 72.5 kV: 229-354 MVA, 5-Finch



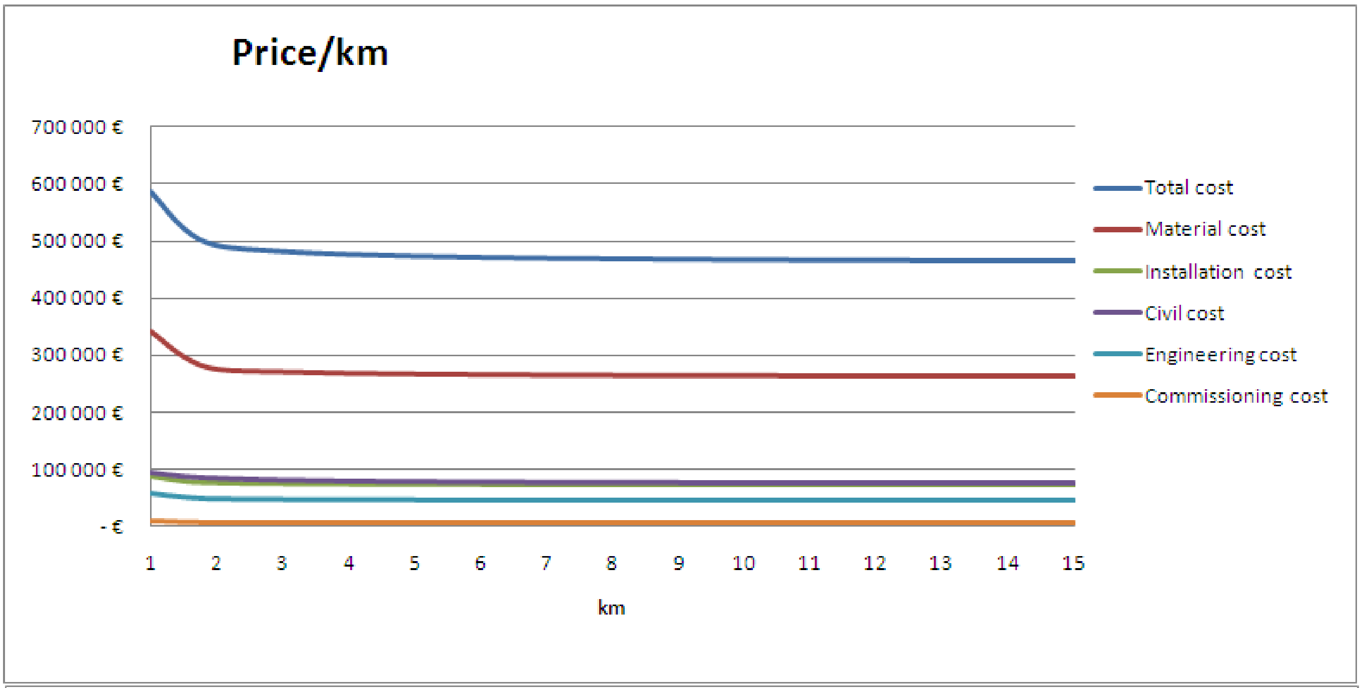


Appendix 12. 72.5 kV: 354-425 MVA, 6-Finch

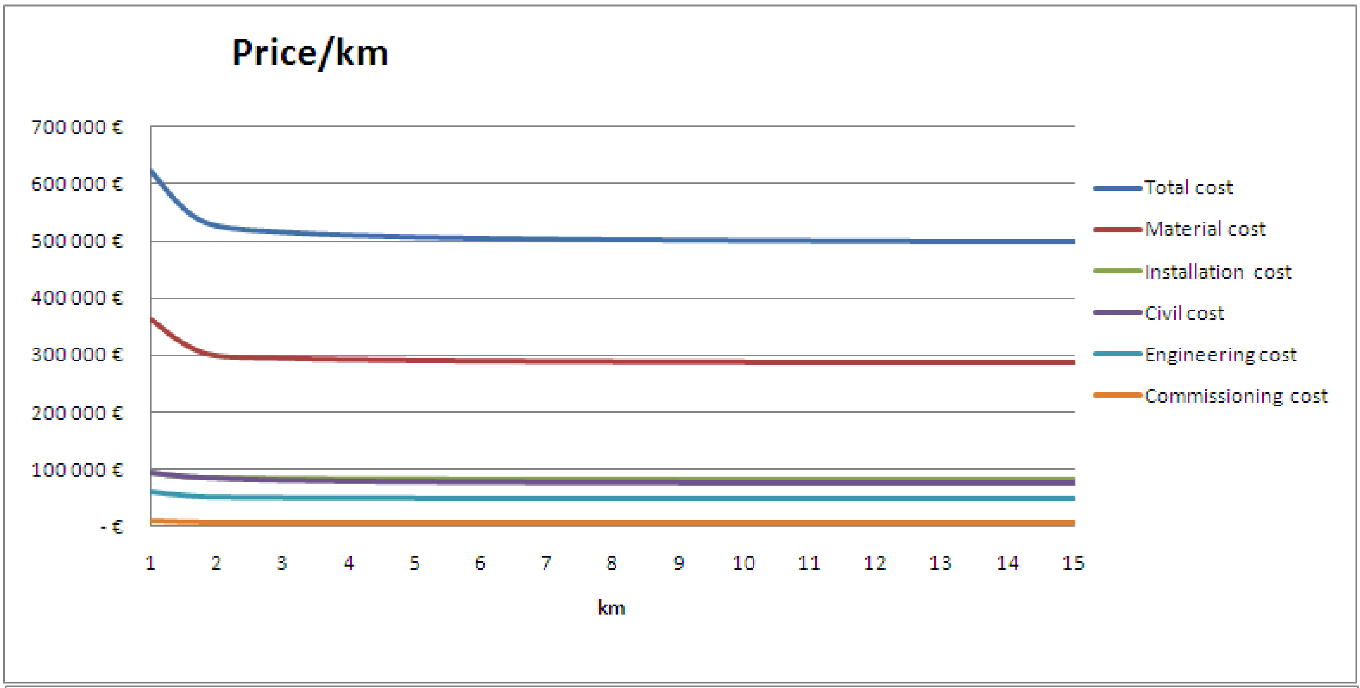




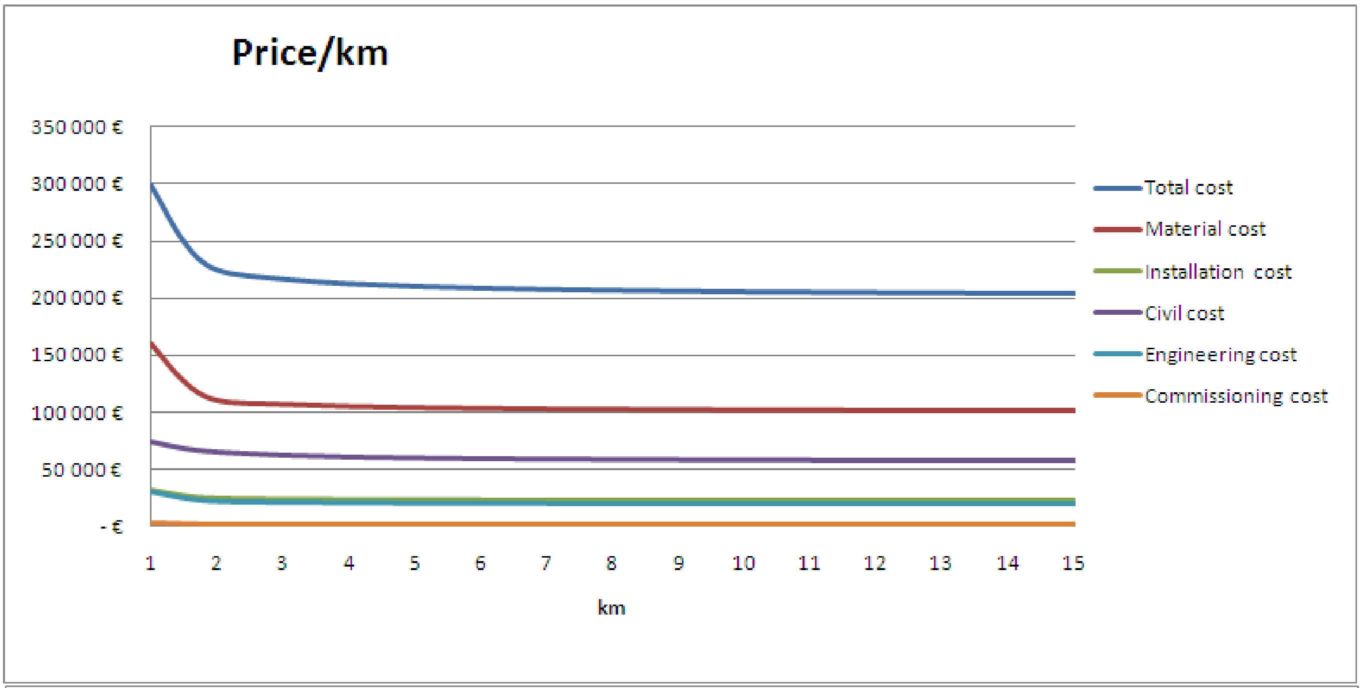
Appendix 13. 72.5 kV: 425-496 MVA, 7-Finch

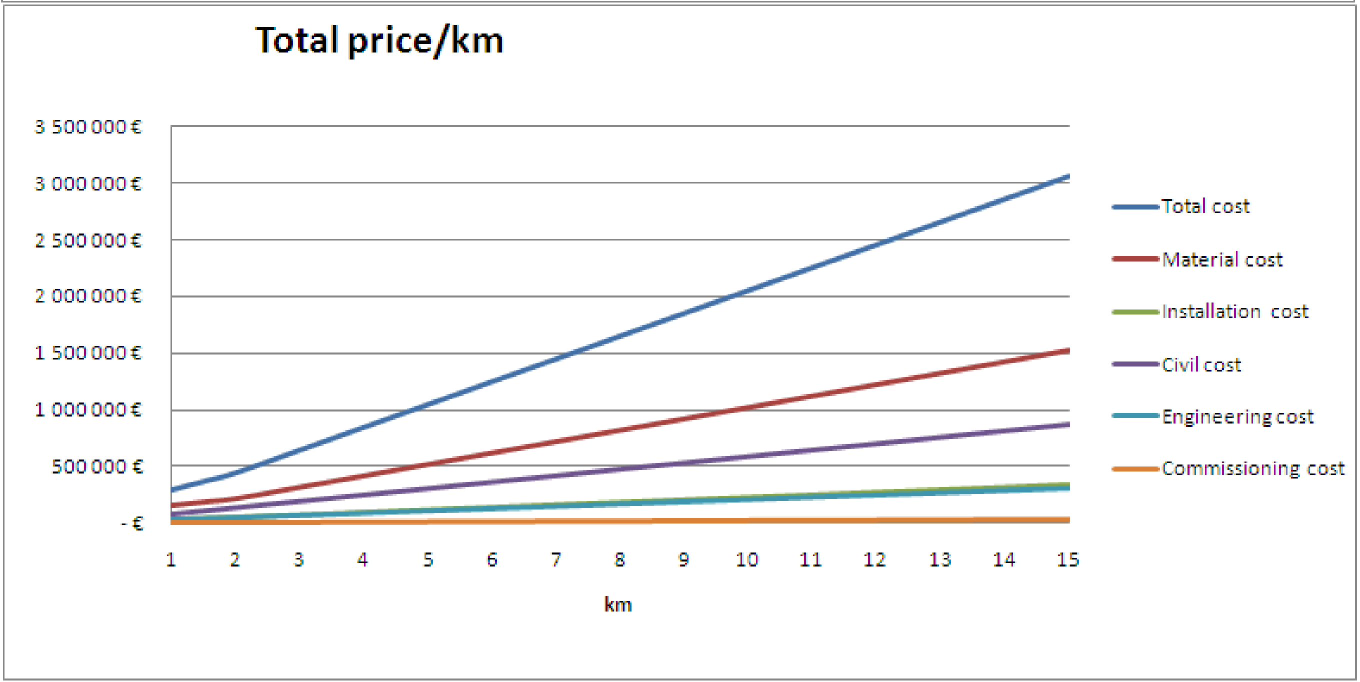


Appendix 14. 72.5 kV: 496-567 MVA, 8-Finch

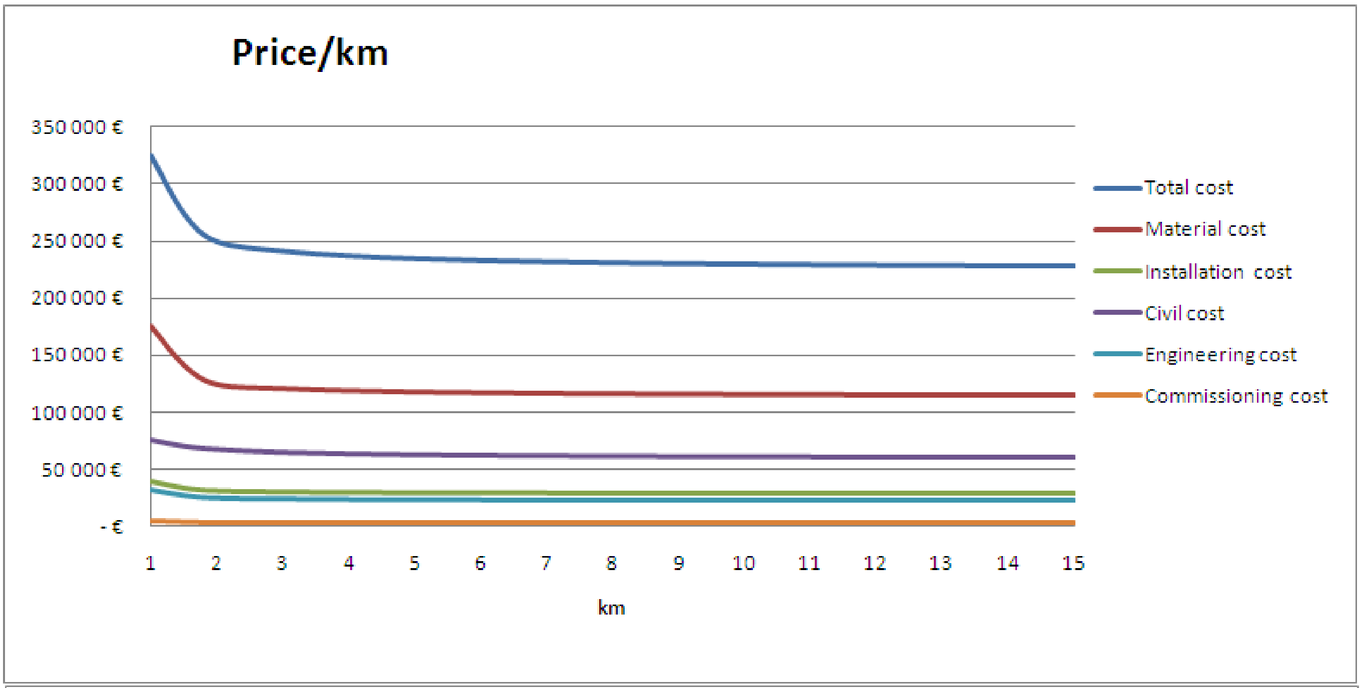


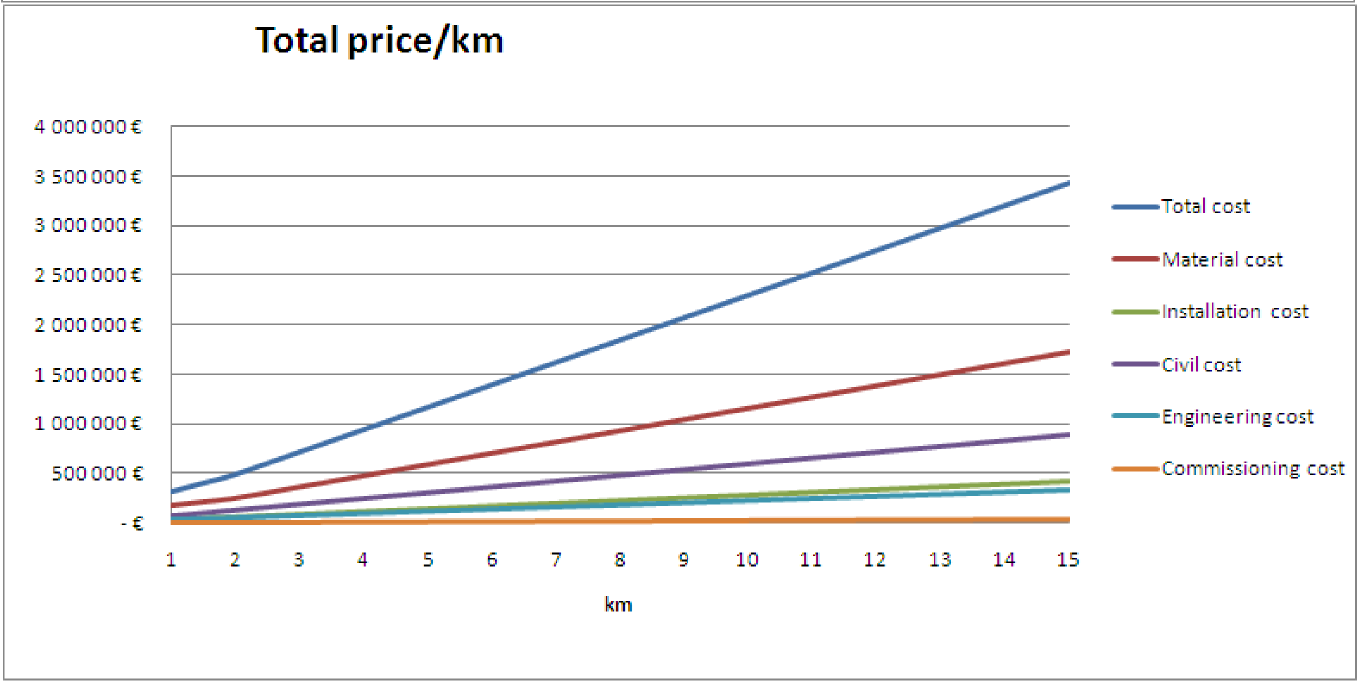
Appendix 15. 145 kV: 0-76 MVA, 1-Duck



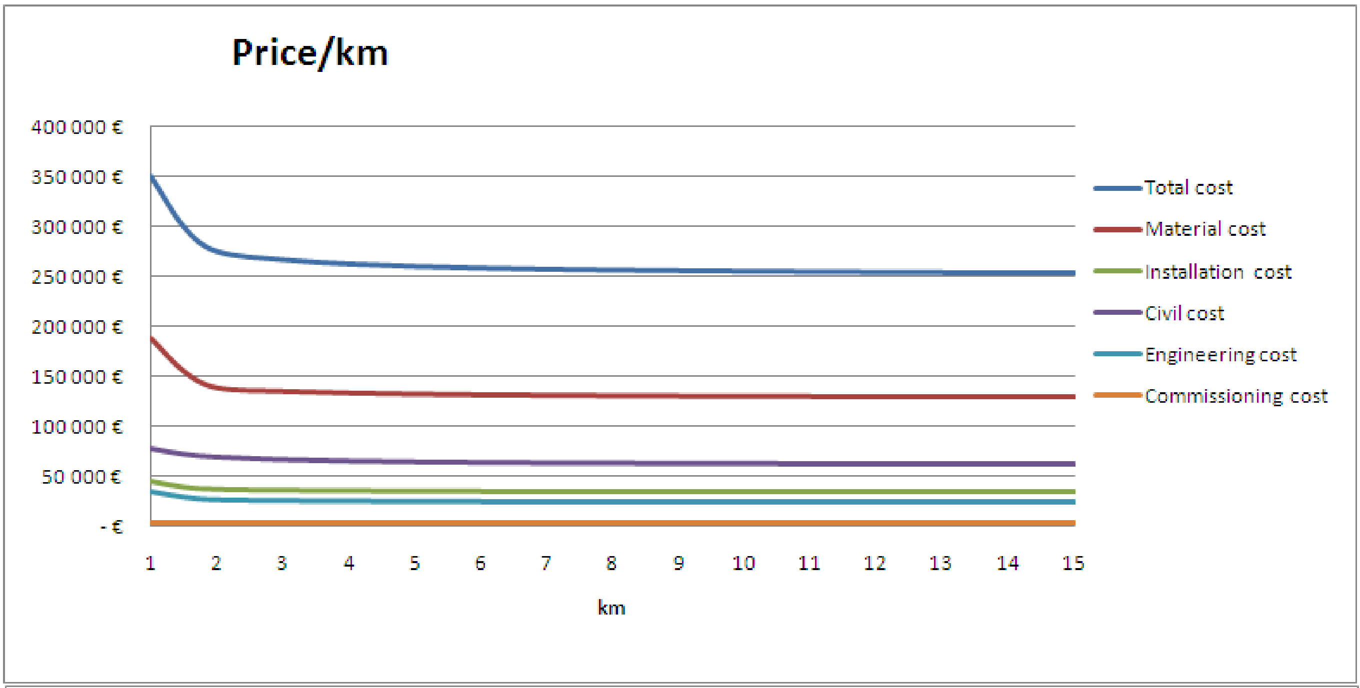


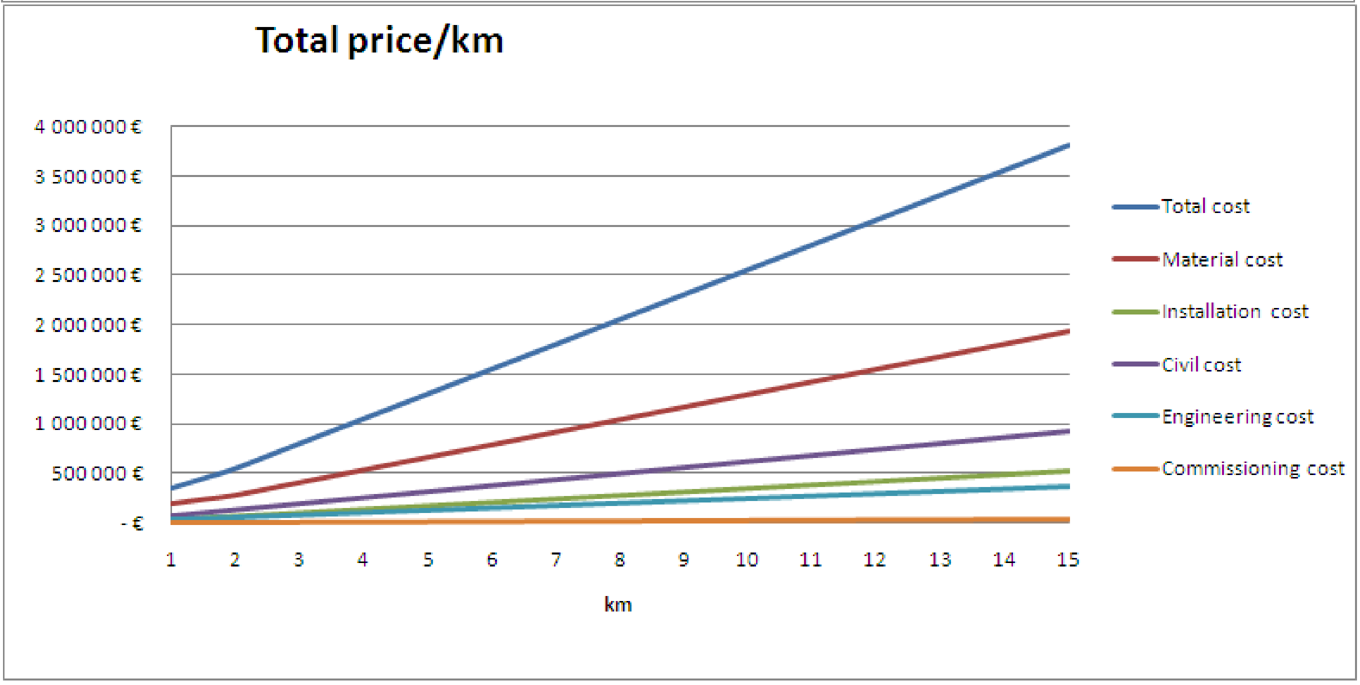
Appendix 16. 145 kV: 76-153 MVA, 2-Duck



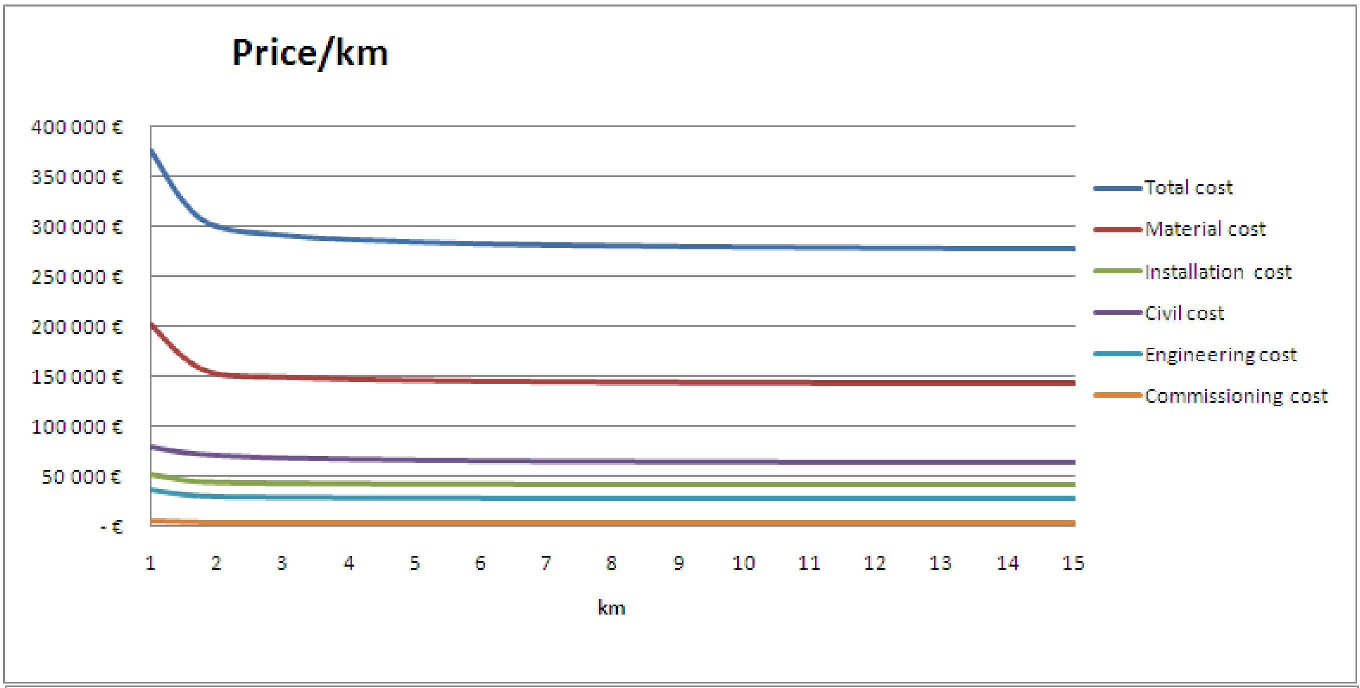


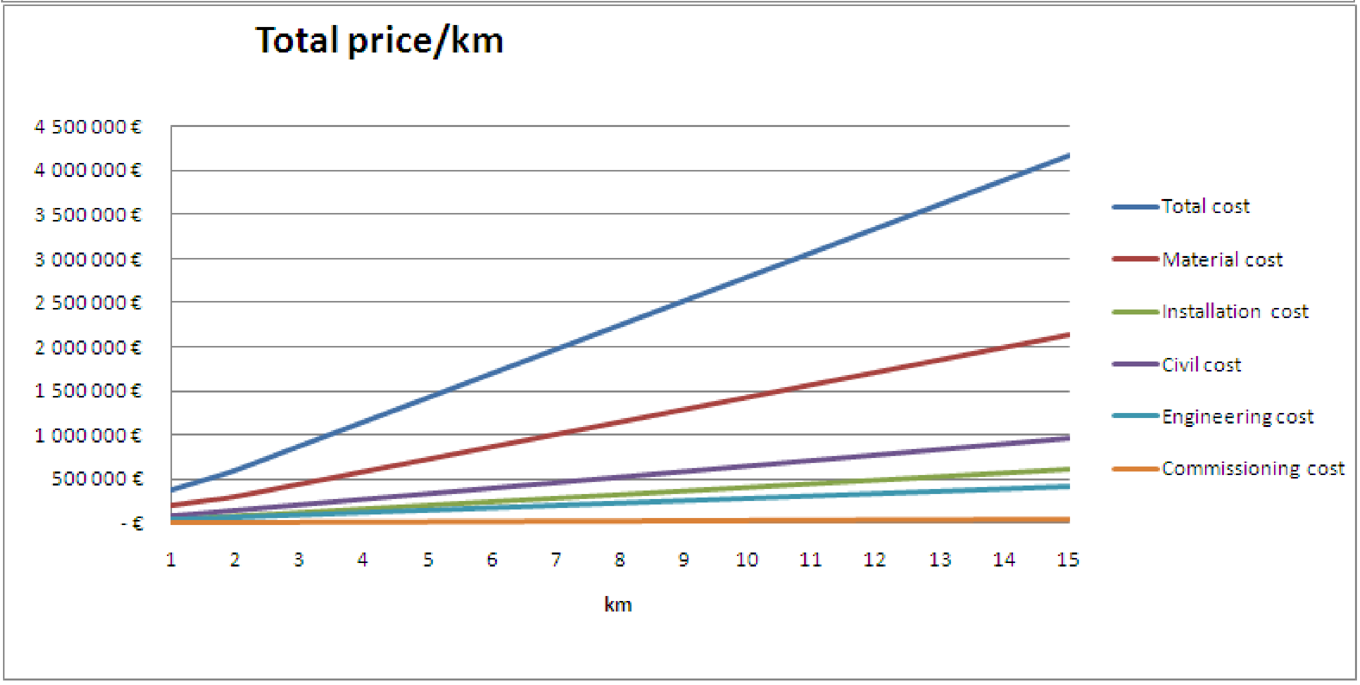
Appendix 17. 145 kV: 153-229 MVA, 3-Duck



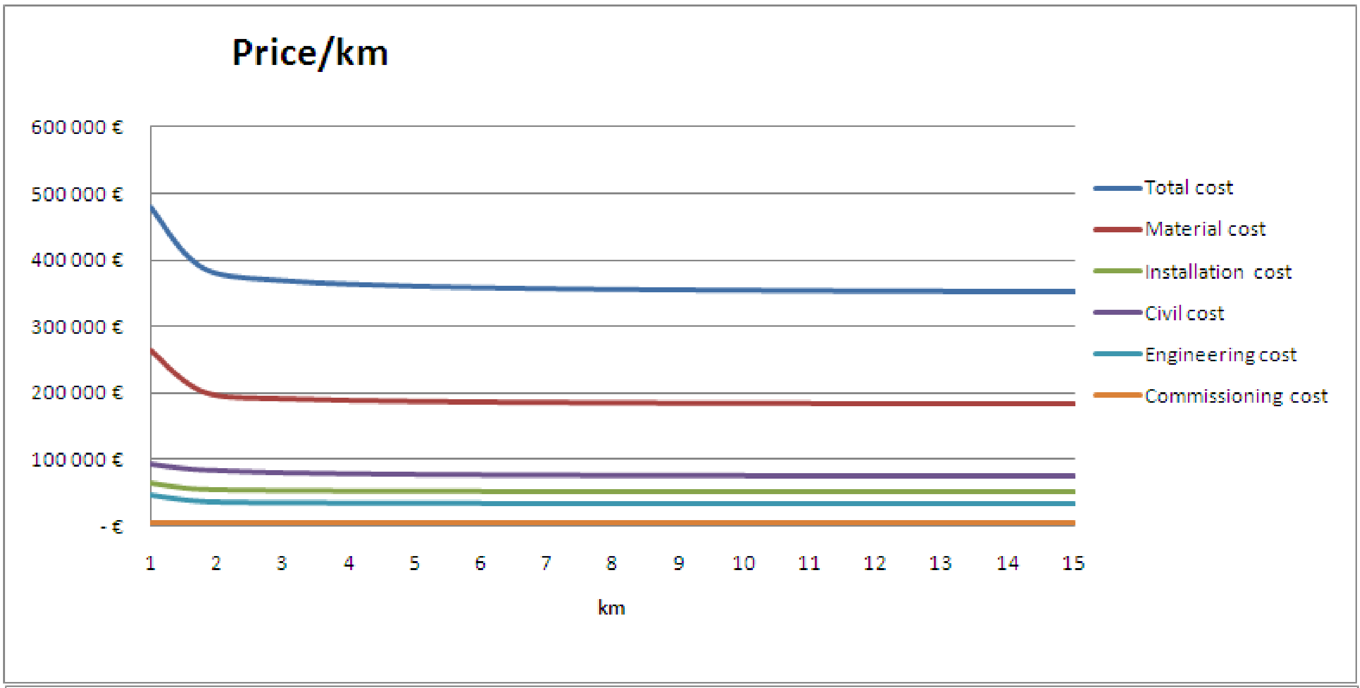


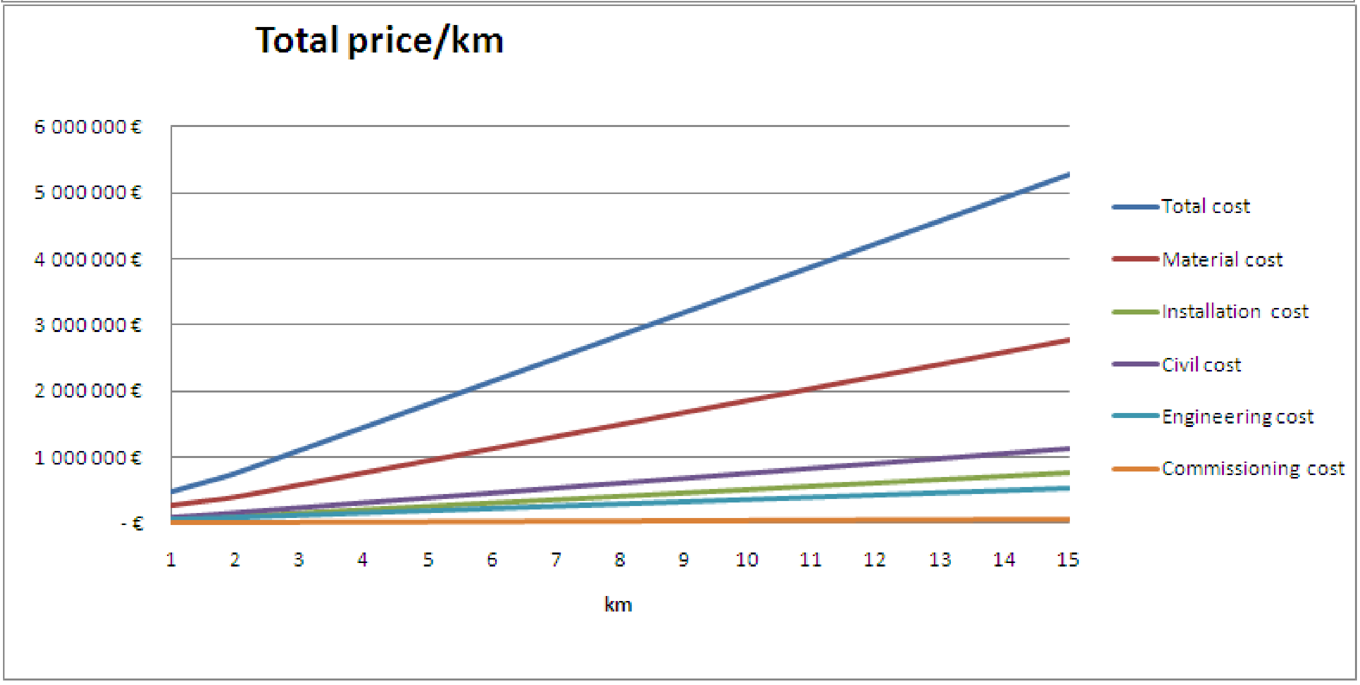
Appendix 18. 145 kV: 229-306 MVA, 4-Duck



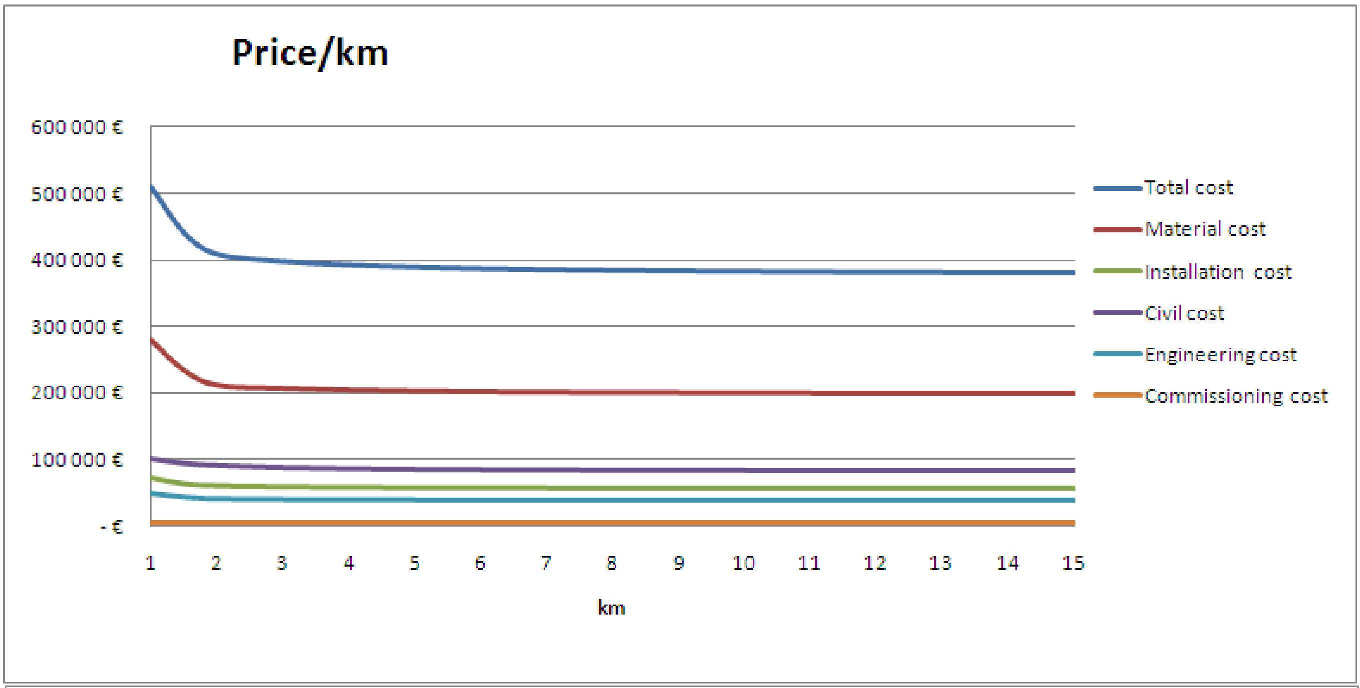


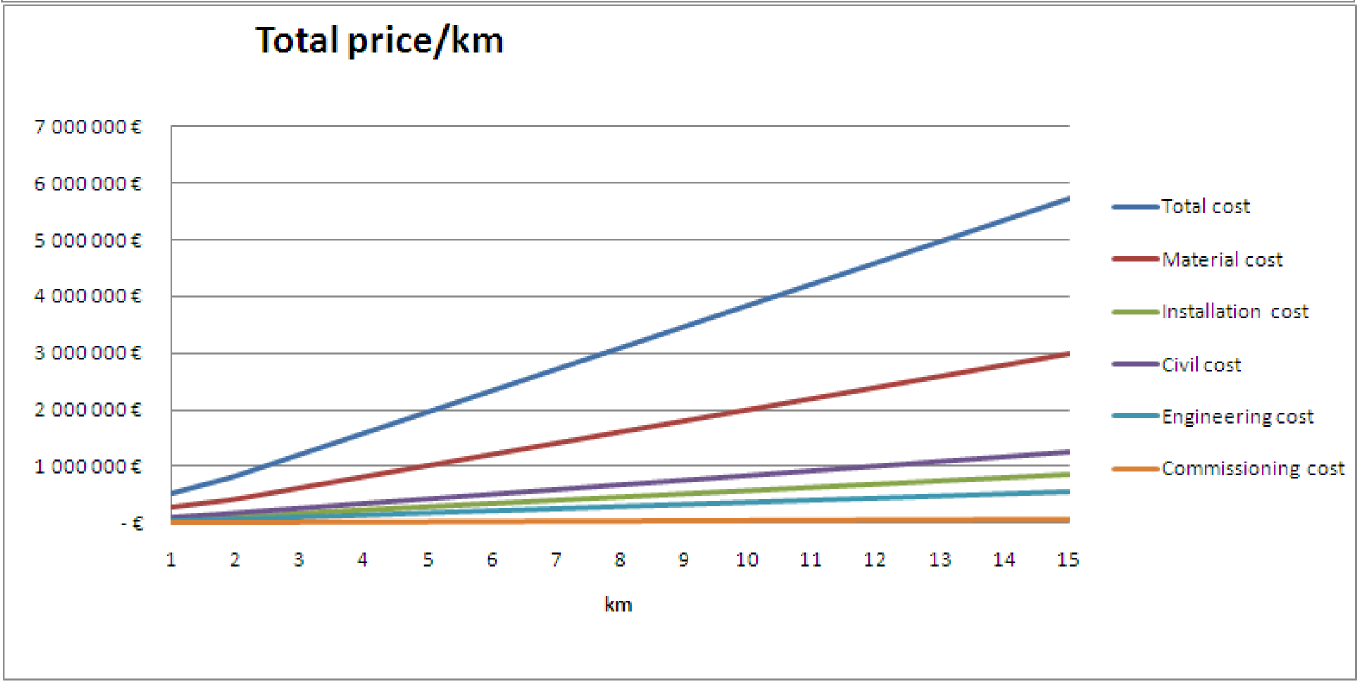
Appendix 19. 145 kV: 306-382 MVA, 5-Duck



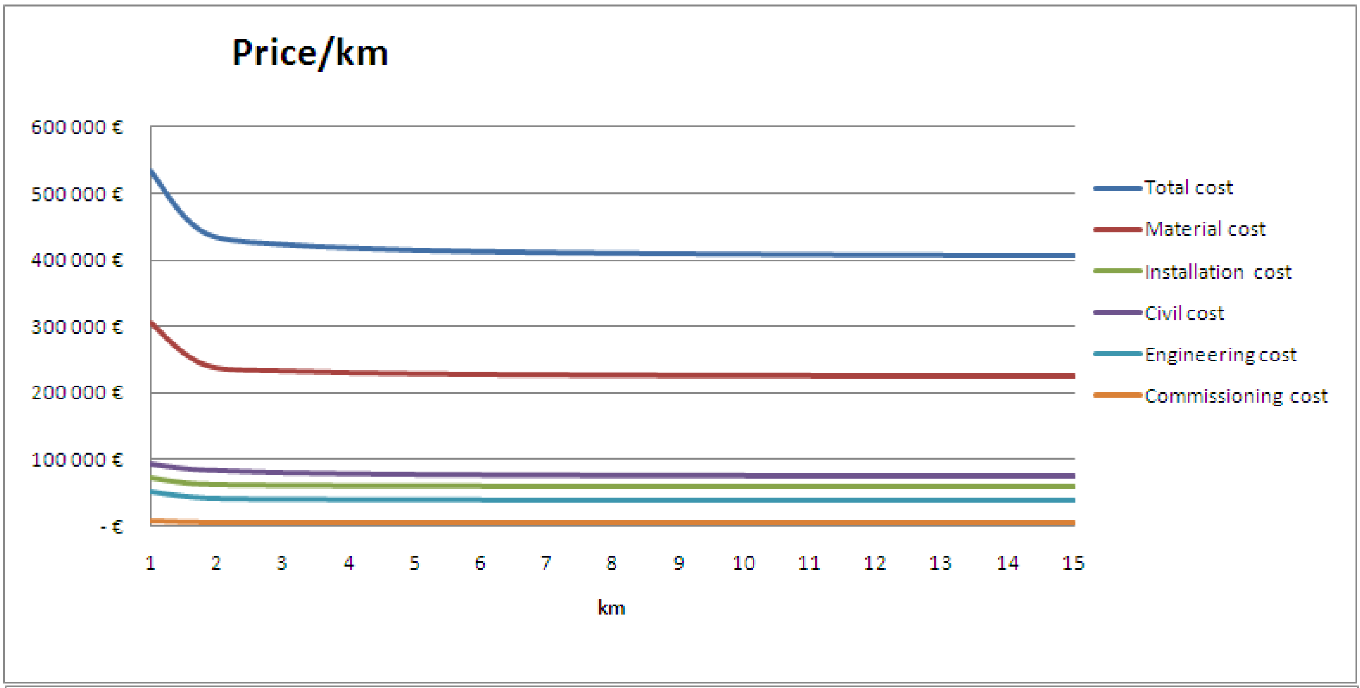


Appendix 20. 145 kV: 382-459 MVA, 6-Duck

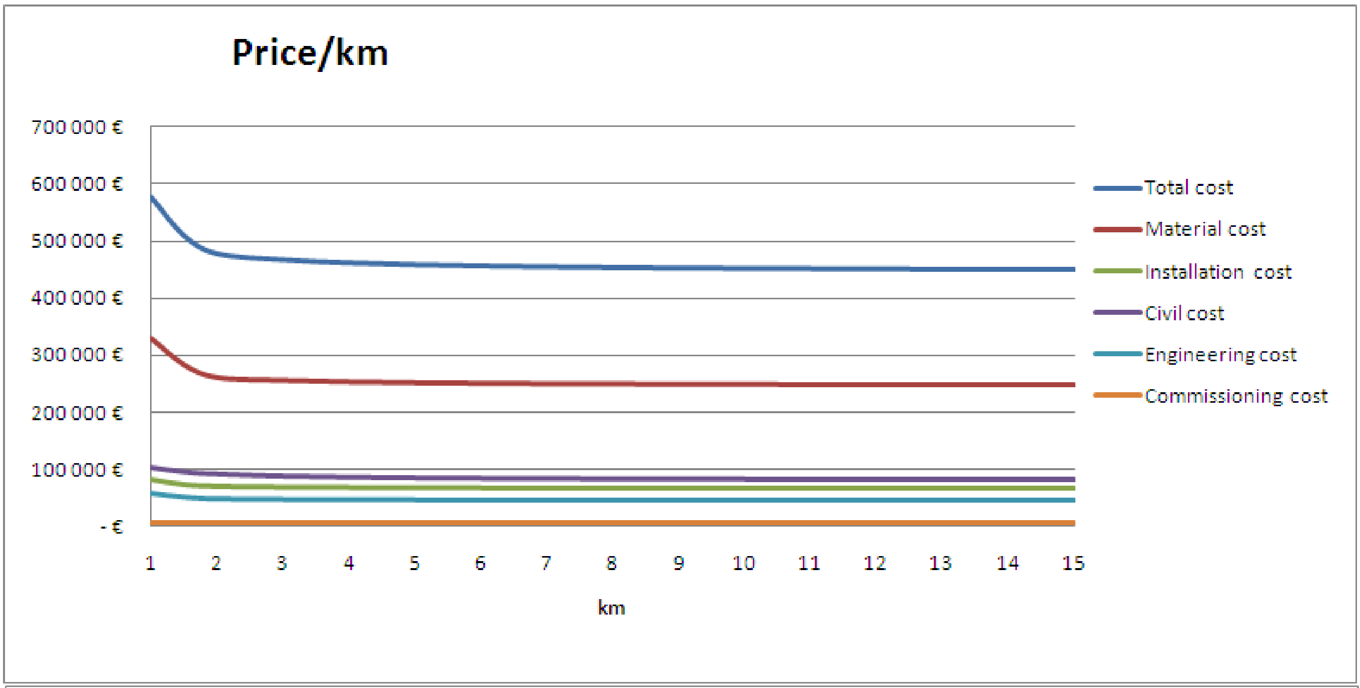


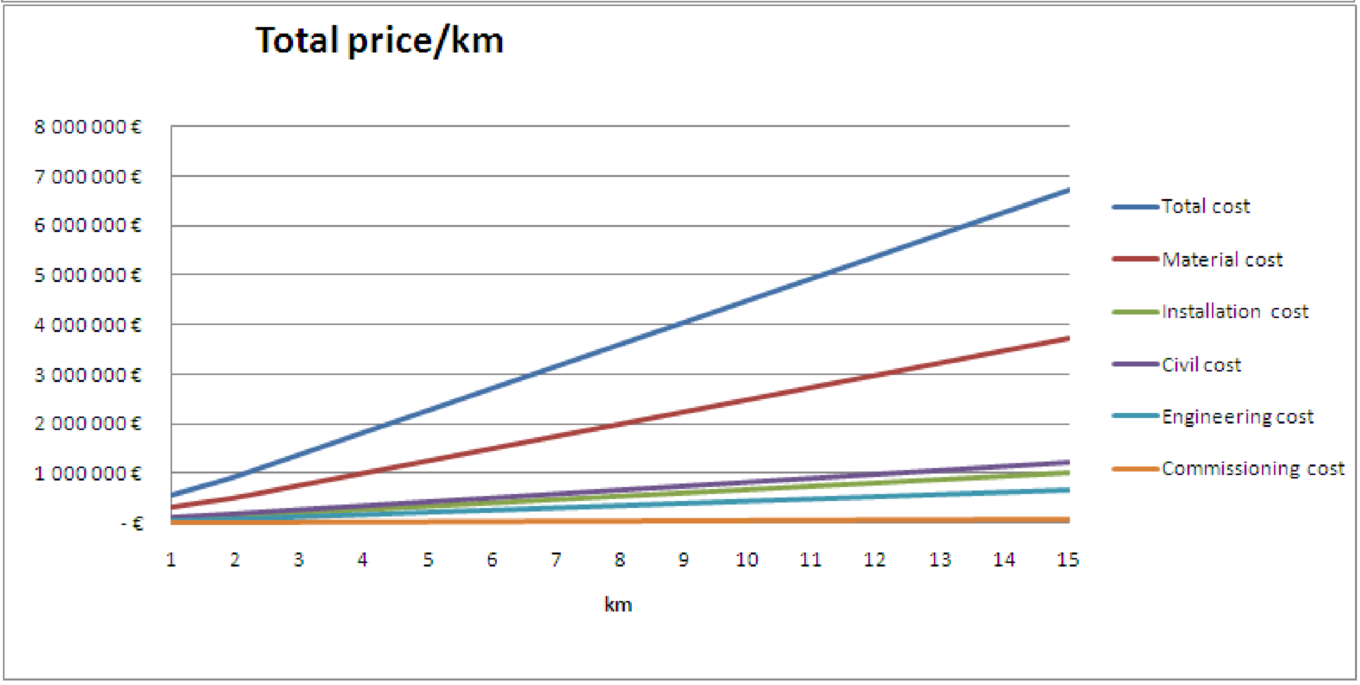


Appendix 21. 145 kV: 459-709 MVA, 5-Finch

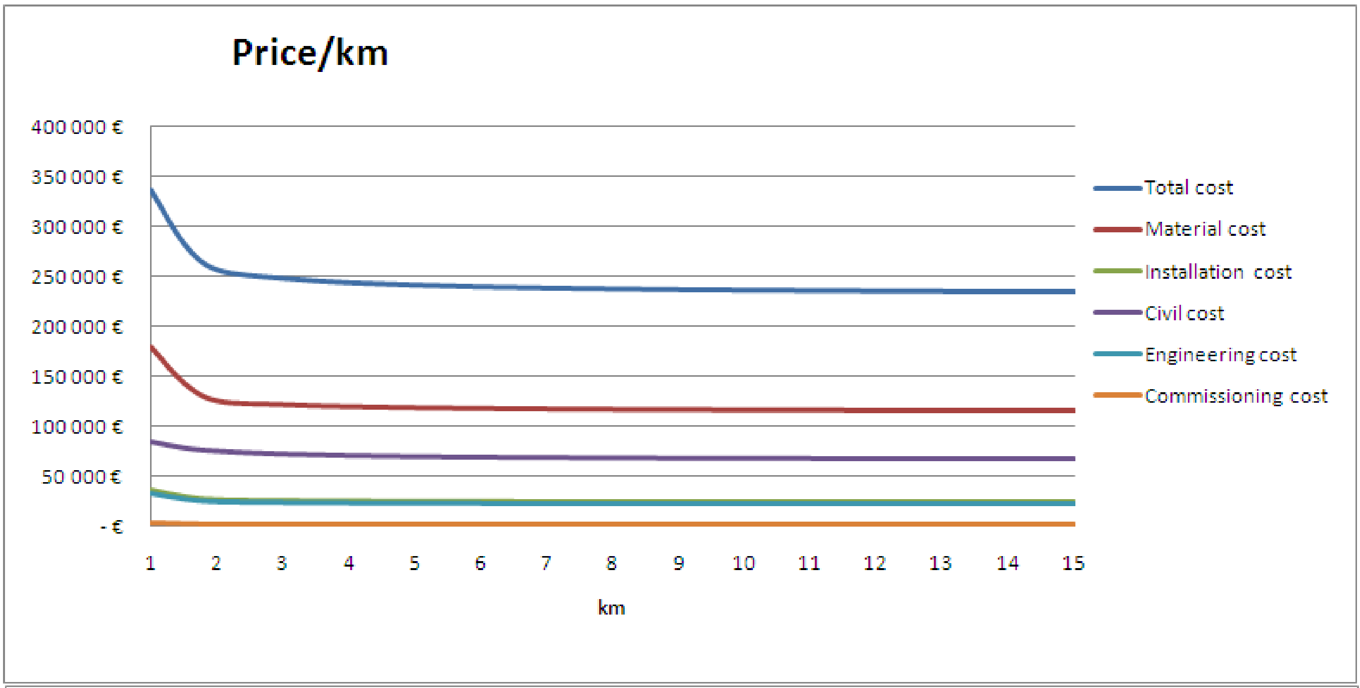


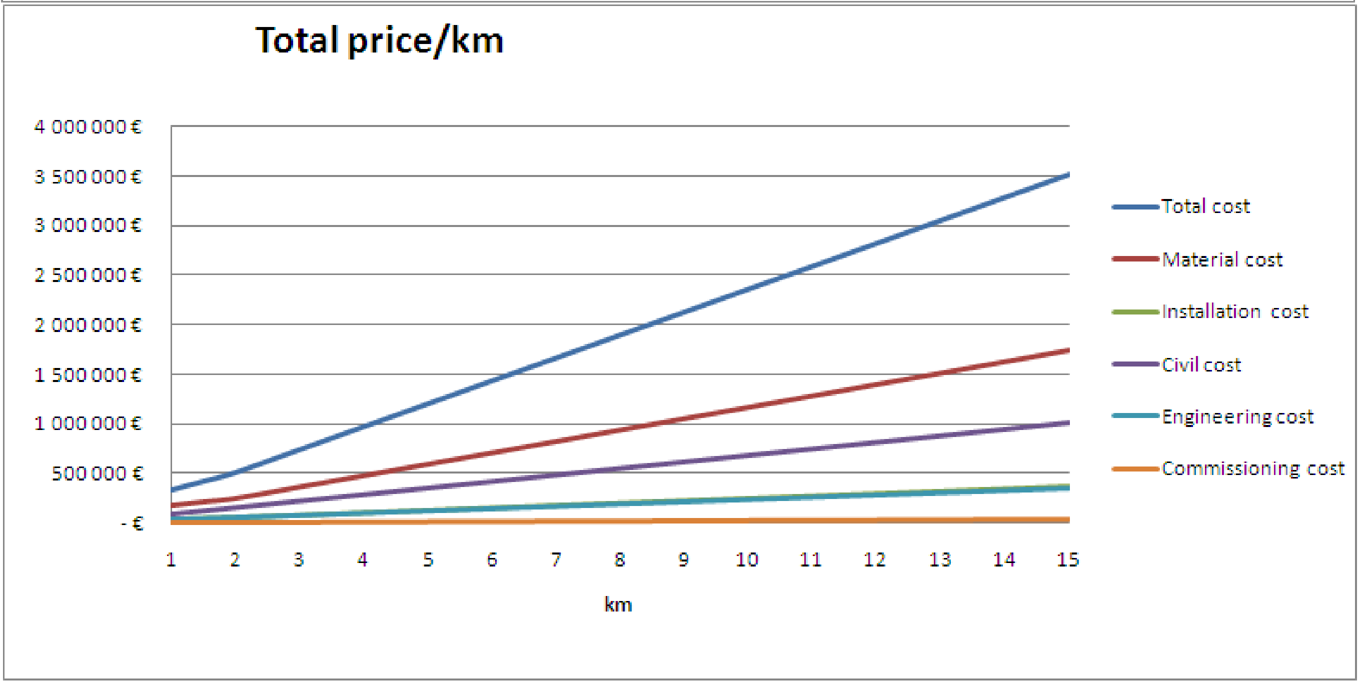
Appendix 22. 145 kV: 709-750 MVA, 6-Finch



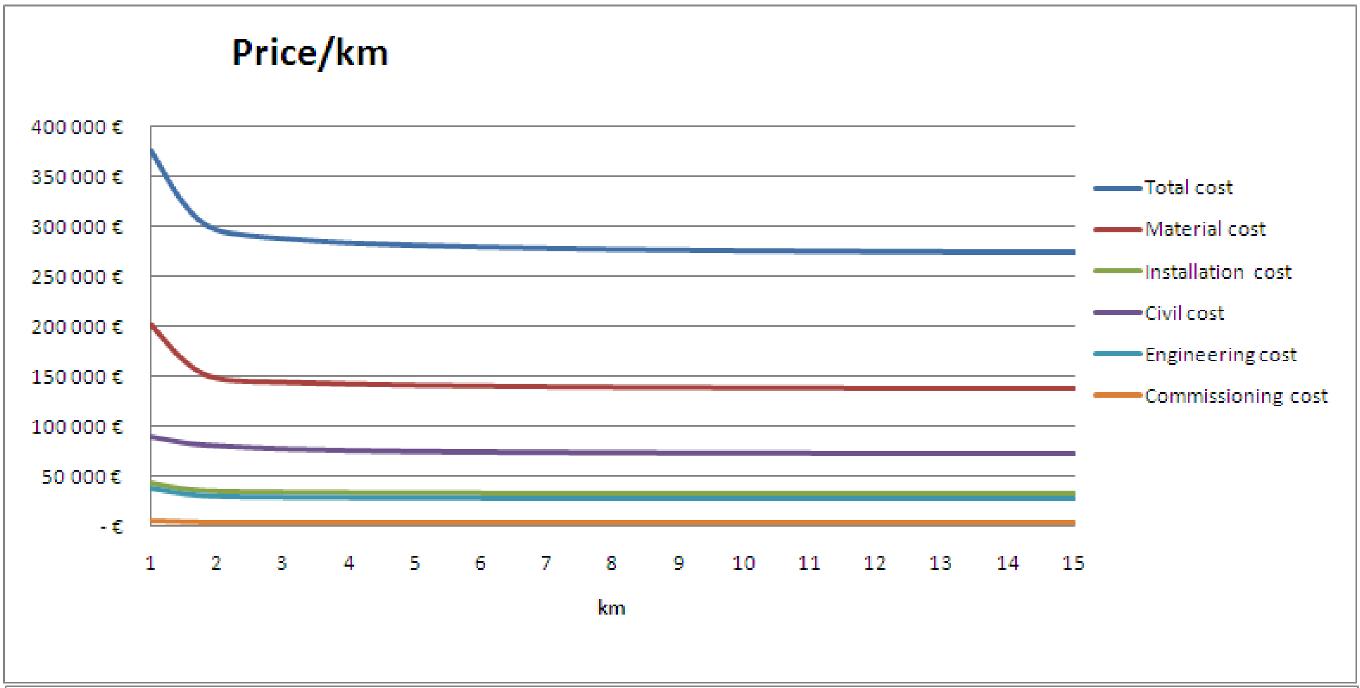


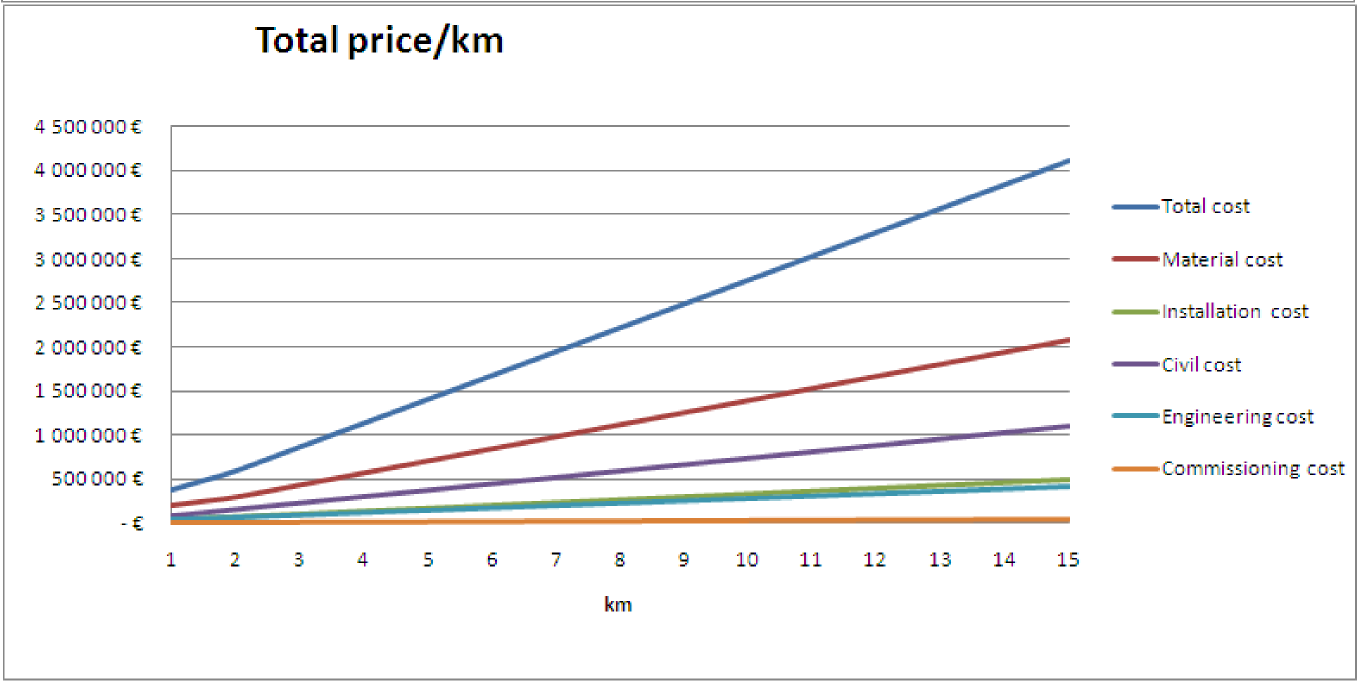
Appendix 23. 245 kV: 0-239 MVA, 1-Finch



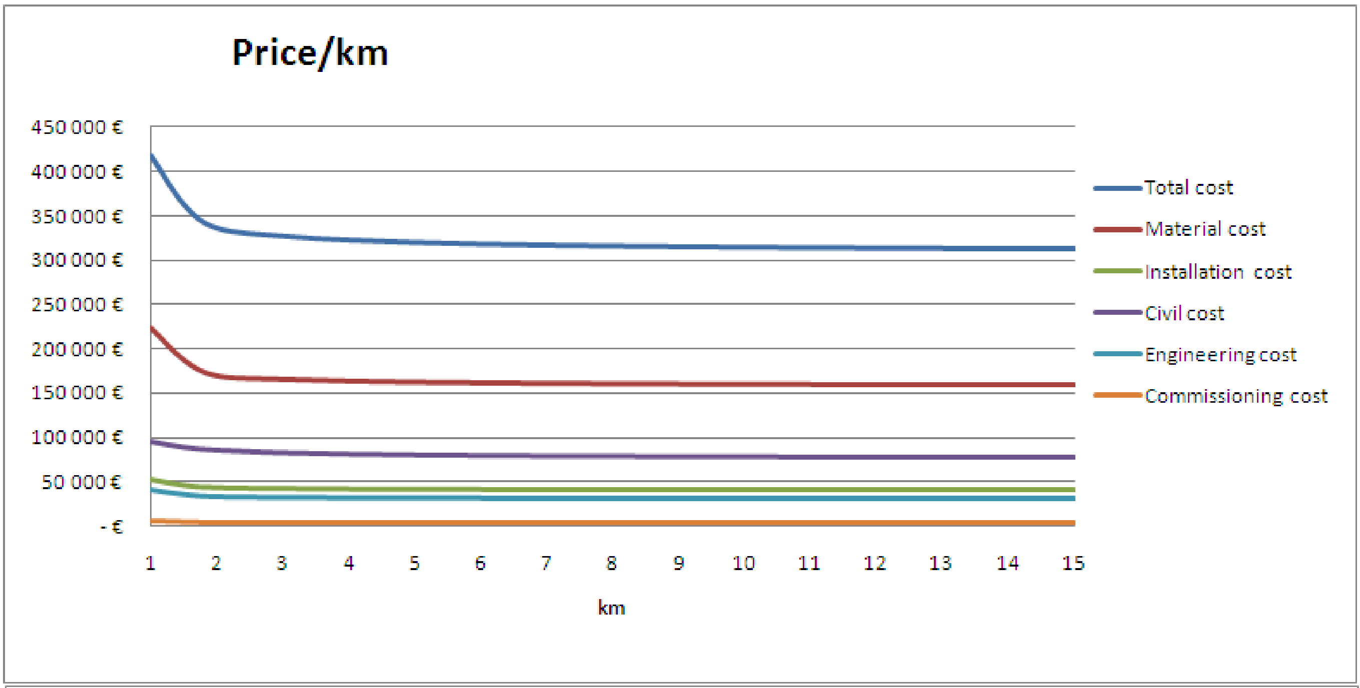


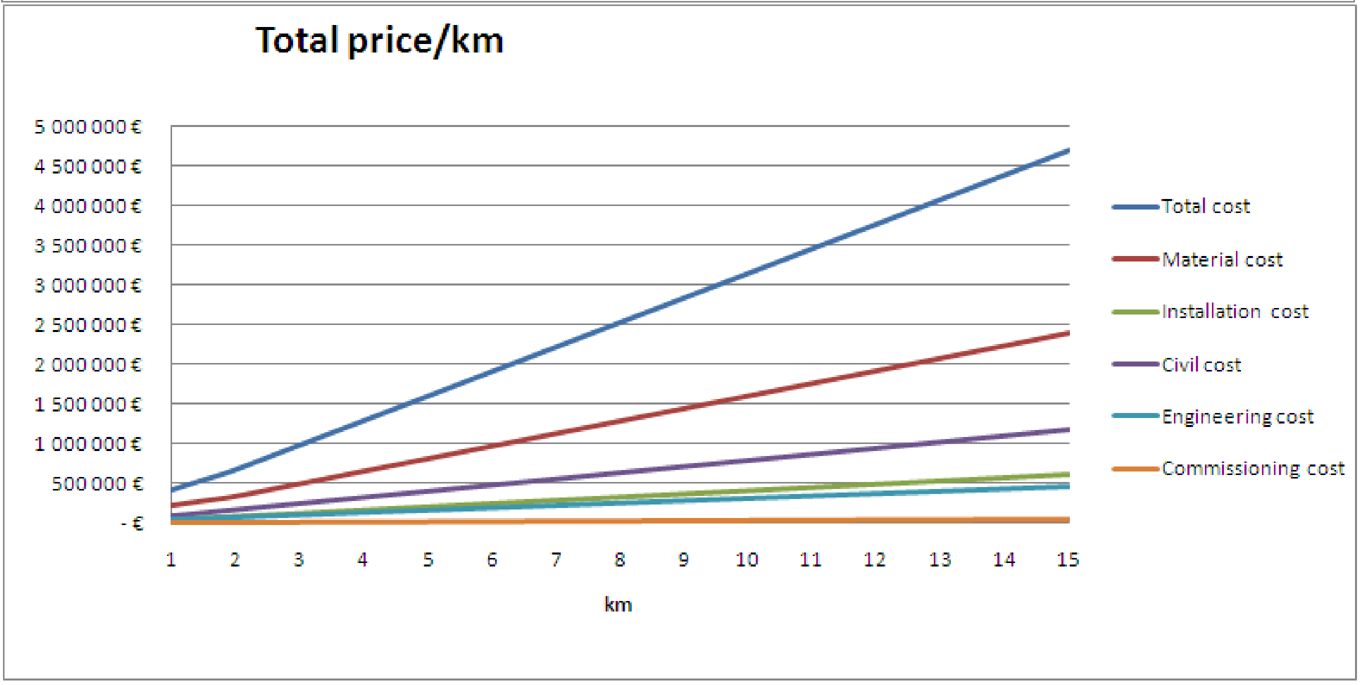
Appendix 24. 245 kV: 239-479 MVA, 2-Finch



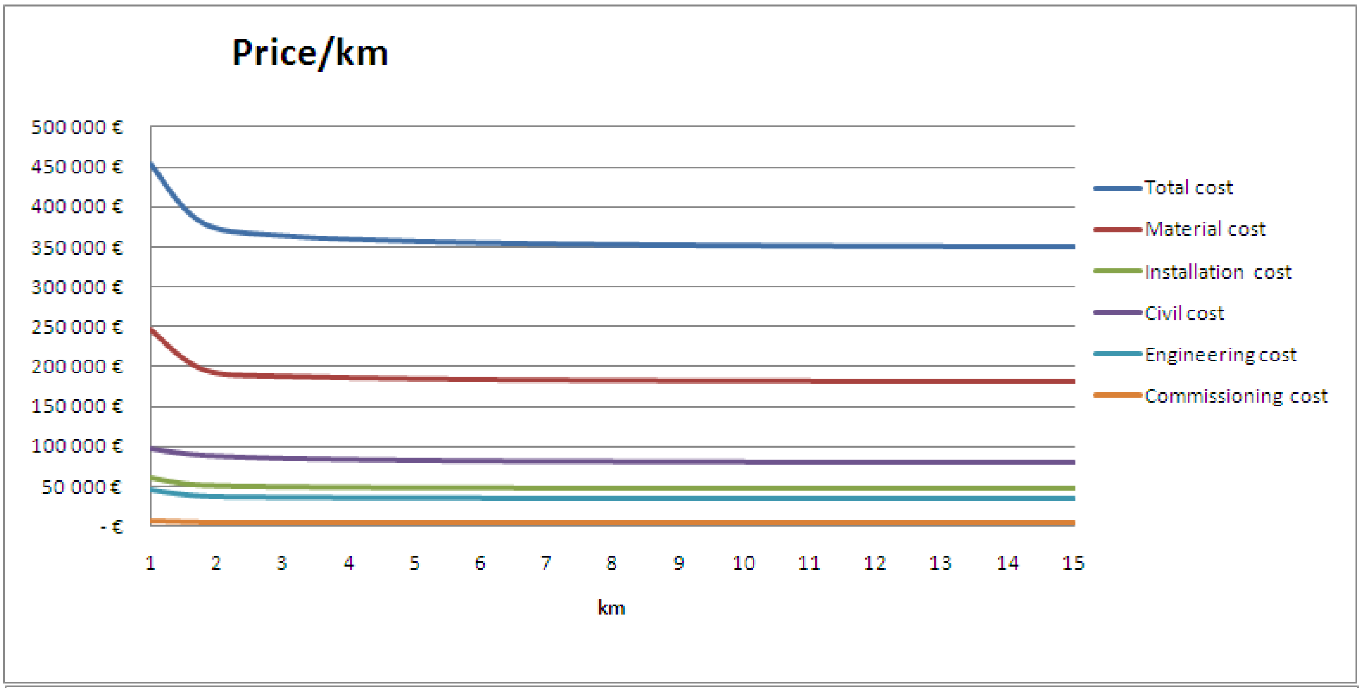


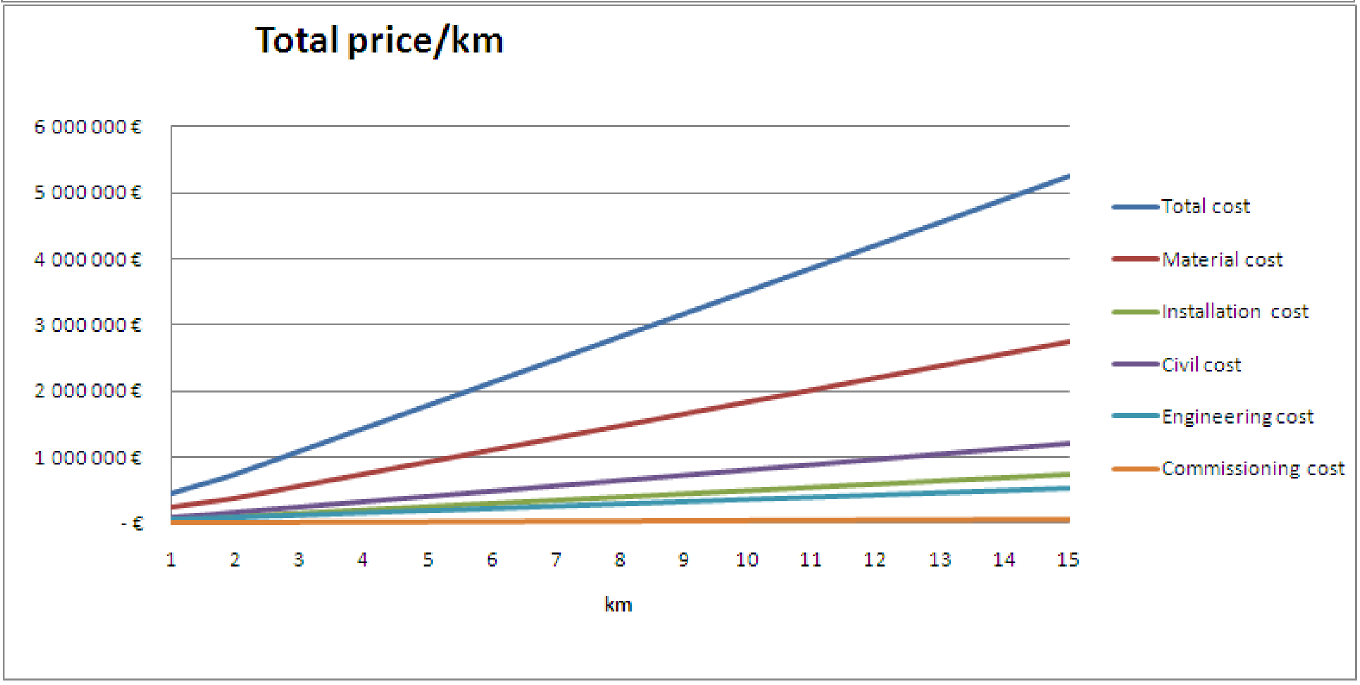
Appendix 25. 245 kV: 479-719 MVA, 3-Finch



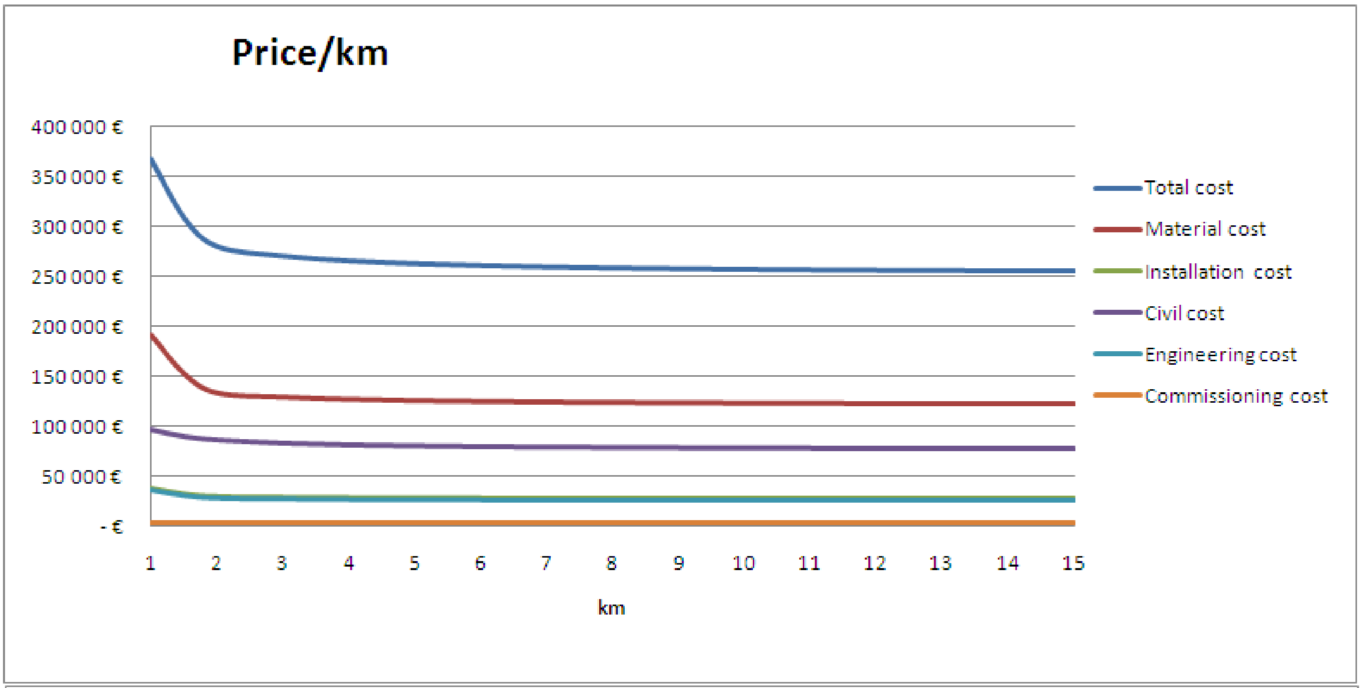


Appendix 26. 245 kV: 719-750 MVA, 4-Finch





Appendix 27. 400 kV: 0-391 MVA, 1-Finch



Appendix 28. 400 kV: 391-750 MVA, 2-Finch