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Economic Comparison of HVAC and HVDC Solutions for Large Offshore Wind Farms under Special Consideration of Reliability

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Abstract

An economic comparison of several HVAC-HVDC transmission systems from large offshore windfarms is presented. The power output from the offshore windfarm is modeled by an aggregated power curve. The transmission cost for several transmission systems is calculated for a wide range of windfarm's rated powers, transmission distances and average wind speeds. Energy losses, energy availability and investment costs constitute the input parameters to the study. For the calculation of the energy availability an algorithm that takes in account the aggregated model of the windfarm and the probability distribution of the wind speed is introduced. The availability study is based on statistical data concerning the reliability of the components of HVAC-HVDC transmission systems.

Acknowledgements

Many thanks to my supervisor Dr. Thomas Ackermann for his trust and support, to Professor Lennart Söder for his valuable comments and to my colleagues and friends Jovan Todorovic, Nicola Barberis Negra, Florent Maupas and John Humphrey for their help and cooperation.

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Introduction

1.1 Problem Backround

In the recent years many offshore windfarm project have been erected and several other are in the process of being commissioned. Their recent size is up to 165.5 MW but plans on 1000 MW windfarms exist. These wind parks are to be located out in the sea at such a distance that will not be detected visually from shore. Projects of this extent require large investments and constitute major economical risks. Thus it is important that a very detailed study concerning the different technical and economical alternatives should be made before the project is commissioned. The purpose of this study is to compare and evaluate different transmission systems from large offshore windfarms on an economical basis. The size of the windfarm varies between 400 and 1000 MW and their distance from the shore is between 50 and 300 km. Three different transmission technologies are in focus:

- HVAC (High Voltage AC)
- HVDC LCC (High Voltage DC with Line Commutated Converters)
- HVDC VSC (High Voltage DC with Voltage Source Converters)

A model that calculates the energy transmission cost of several transmission systems is introduced. The major inputs to this model are:

- The average losses in the transmission system
- The energy unavailability of the transmission system as a result of forced outages (failures) in the transmission system
- The investment cost for constructing the transmission system

1.2 Wind Power System's Historical Background

Wind energy is not something that has been recently discovered. Traces of man trying to harness the wind can be spotted throughout human history. Different designs of early windmills can be found with respect to the application used for, the technology of the time and the culture of the area that they were built in.

Figure 1.1:A typical Dutch windmill

Figure 1.2:The Mediterranean windmill

The integration of wind power into the industrial environment, as a reliable source of large scale electrical energy production, is rather recent. The awareness that fossil fuel deposits are becoming shorter and the increasing environmental concerns, in combination with technological maturity pushed the development of wind power systems. Today wind power is considered to be one of the fastest growing forms of electrical energy production.

1.3 Wind Turbines

The basic unit of all wind power systems is the wind turbine. Almost all wind turbines producing electricity consist of rotor blades which rotate around the horizontal hub. The hub is connected to the gearbox and the generator, which are located inside the nacelle. The nacelle houses the electrical and mechanical components and is mounted at the top of the tower. The rotor diameter range up to 124 m and the wind turbines can have three (most common), two or one blades.

Power is controlled automatically as wind speed varies and the turbines are stopped at very high speed (cut out speed). Towers are mostly cylindrical and made of steel with their height ranging from 25 m up to more than 100 m.

Figure 1.3: The Vestas V90 3 MW wind turbine

Commercial turbines range in capacity from a few hundred kilowatts to 5 MW. The crucial parameter is the diameter of the blades. The longer the blades, the larger the area swept by the rotor and the greater the energy output. Improvements in technology continue to make turbines larger and more efficient while the cost of energy production decreases.

There are two main methods of controlling the power output from the rotor blades. The angle of the rotor blades can be actively adjusted by the machines control system. This is known as pitch control. In the other method, which is known as stall

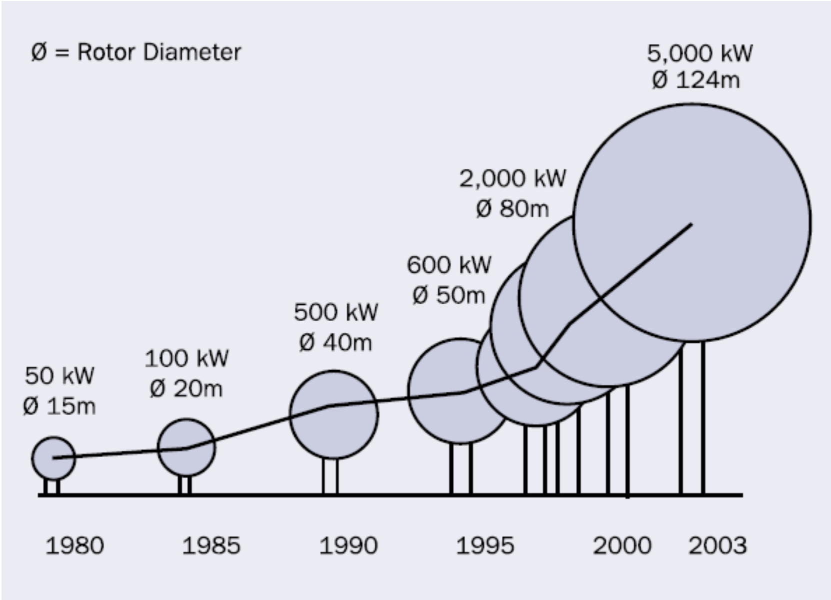


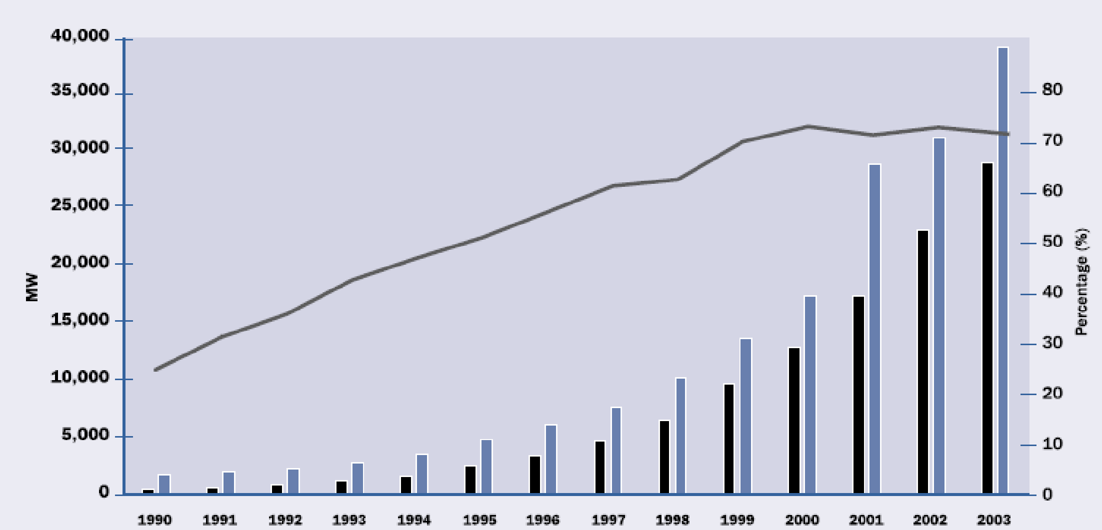
Figure 1.4: Growth of commercial wind turbines (source EWEA [1.1])

control, no moving parts exist. This method is sometimes known as passive control since it is the inherent aerodynamic properties of the blade which determine the power output. The twist and thickness of the rotor blade vary along its length, in such a way that turbulences occur behind the blade whenever the wind speed becomes too high. (For detailed information about wind turbine characteristics and features see [1.2])

1.4 Wind Energy: Present-Future

Although conventional methods of power dominate the energy needs worldwide, energy production from wind power systems shows an increase with Europe having the leading position. Today wind energy projects across Europe produce enough electricity to meet the domestic needs of 5 million people. The European Wind Energy Association (EWEA) has set a goal for 75,000 MW and 180,000 MW of wind energy capacity to be installed by 2010 and 2020 respectively [1.3].

The above mentioned targets if achieved will have multiple benefits. The reduction of CO_2 emissions, from the replacement of fossil fuel electricity production will be according to [1.3] 109 million tones annually while the cumulative avoided fuel cost can reach the amount of 13.2 million € until 2010. The wind power industry will flourish creating many employment opportunities and the large amount of investments planned can create the perfect environment for further evolution of the technology surrounding wind power.



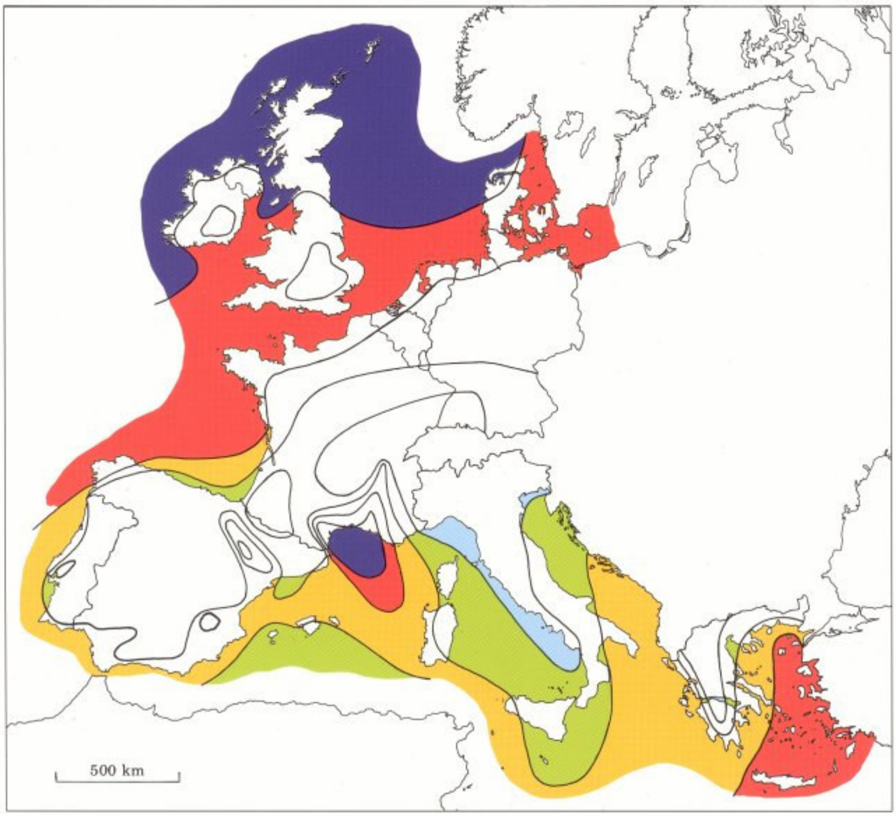
	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003
EU-15	439	629	844	1,211	1,683	2,497	3,476	4,753	6,453	9,678	12,887	17,315	23,098	28,440
WORLD	1,743	1,983	2,321	2,801	3,531	4,821	6,104	7,636	10,153	13,594	17,357	28,857	31,128	39,500
EU % of world	25	32	36	43	48	52	57	62	64	71	74	73	74	72

Figure 1.5:EU and Global Cumulative Installed Wind Capacities 1990-2003, [1.3]

1.5 Potential of Energy Production by Offshore Windfarms

In the past decade wind power systems have gone through investigation to implementation. Wind farms are no logger experimental facilities but large commercially based units. The technology is mature for installation of large scale wind power systems. In Europe, though, land limitations in areas with high population density exist and most of the onshore exploitable locations are already in use. Furthermore, in some countries the public would no longer accept a significant increase in onshore wind power capacity. All these create a significant problem, constraining further wind energy development in many parts of Europe.

Offshore, however, there is a large wind resource that has the advantage of both abundant space and dense winds. The energy in the wind increases with the cube of the wind speed (10% increase in the wind speed will result in 30% increase in energy) [1.5]. Thus, since in offshore locations wind speeds are relatively higher than onshore, going offshore gives significantly higher electrical energy output. In 2001 the annual offshore wind potential was estimated to be 8.5 PWh in Europe [1.6].



Wind resources over open sea (more than 10 km offshore) for five standard heights										
	10 m		25 m		50 m		100 m		200 m	
	$m s^{-1}$	Wm^{-2}	$m s^{-1}$	Wm^{-2}	$m s^{-1}$	Wm^{-2}	$m s^{-1}$	Wm^{-2}	$m s^{-1}$	Wm^{-2}
	> 8.0	> 600	> 8.5	> 700	> 9.0	> 800	> 10.0	> 1100	> 11.0	> 1500
	7.0-8.0	350-600	7.5-8.5	450-700	8.0-9.0	600-800	8.5-10.0	650-1100	9.5-11.0	900-1500
	6.0-7.0	250-300	6.5-7.5	300-450	7.0-8.0	400-600	7.5- 8.5	450- 650	8.0- 9.5	600- 900
	4.5-6.0	100-250	5.0-6.5	150-300	5.5-7.0	200-400	6.0- 7.5	250- 450	6.5- 8.0	300- 600
	< 4.5	< 100	< 5.0	< 150	< 5.5	< 200	< 6.0	< 250	< 6.5	< 300

Figure 1.6: EU offshore wind map (source: Riso National Laboratory Denmark)

The largest problem of building an offshore wind farm is the high cost. Not only the cost for the wind farm itself (transportation of components, foundation, electrical grid) but also the transmission system to the onshore grid are significantly higher offshore than onshore. Specially designed and very expensive constructions, as offshore platforms that will host large components of the transmission system (transformers, converter stations), will be required. All the equipment installed have to be designed to meet higher standards in order to be efficient in the highly corrosive offshore environment. Maintenance, both in the wind farm and the transmission system, will require highly trained personnel using costly transportation means (helicopters, ships specifically designed for this purpose). In many cases, maintenance can delay significantly due to harsh weather, resulting in great economic losses.

Country	turbines rotor/kW total capacity, lay-out	Distance to shore	Water depth (m)	Foundation	Hub Height (m)	Transmision voltage	Offshore substation	KWh/ m^2/y -kWh/y
Utgrunden /Oland / Sweden	7*Enron Wind 70/1500 10,5 MW / cluster	12 km.	7-10	Driven mono-pille	N/A	20 KV	No	1.370 - 36.900.000
Blyth /United Kingdom	2*Vestas V 66/2.000 4 MW	1 km.	6m-5m.tide	Drilled mono-pille	58	11 KV	No	1.754 - 12.000.000
Middelgrunden/Denmark	20*Bonus 76/2.000 40 MW, curved line	2-3	2-6	Conc-rete caisson	60	30 KV	No	1.100 - 99.000.000
Yttre Stengrund /Oland - Sweden	5*NEG-Micon 72/2000 10 MW / line	5 km	8	Drilled mono-pille	60	20 KV	No	1.475 - 30.000.000
Horns Rev Esbjerg - Denmark	80*Vestas V 80/2.000 160 MW, carré	14-20km.	6-14m.	Drilled mono-pille	70	150 KV	Yes	1.493 - 600.000000
Frederiks-haven Denmark	1*Vestas V 90 - 3.000	500 m.	1	Bucket	80	N/A	No	1200 - 7.600.000
Ronland Jutland-West, Denmark	4*Vestas V 80/2.000 4 Bonus 82/2.3	N/A	N/A	N/A	N/A	N/A	No	1.400 - 60.000.000
Samso, Denmark	10*82,4/2.300 Bonus 23 MW, line	3,5 km	11-18	Mono-pile	61	30 KV	No	1.480 - 78.000.000
Frederiks-haven Denmark	1*Nordex 90 / 2.300 1*Vestas V 90 / 2.000 1*Bonus 82 / 2.300	500 m.	1	N/A / Bucket/ N/A	N/A / 80/ N/A	N/A	No	1200 - 22.000.000
Nysted, Lolland, Denmark	72*Bonus 82/2300 165,6 MW carré	9 km.	6-10	N/A	70	132 KV	Yes	1.600 - 595.000.000
Arklow Bank Irish Sea,Ireland	7*GEW 104/3.600 25 MW	7-12 km	5	Mono-pile	74	38 KV	No	1.600 - 95.000.000
North Hoyle,Wales	30*Vestas V 80/2.000 60 MW	7-8 km.	12 m.-8 m. tide	Mono-pile	67	33 KV	No	1.600 - 240.000000
Scroby Sands Norfolk, UK	30*Vestas V 80-2.000 60 MW	2,3 km.	N/A	N/A	68	33 KV	No	1.600 - 240.000.000

Table 1.1: Table of existing offshore and near shore wind farms built since 2000 [1.7], [1.8]. N/A: not available

In spite of the problems mentioned above, the interest for offshore wind farms was increasing. The first small-scale offshore wind farms were built between 1991 and 1997 in Sweden, Denmark and the Netherlands more as demonstration projects, and were installed in relatively sheltered waters. The year 2000 marked the start of commercial offshore development with the erection of the first sea-based wind farms employing the current generation of megawatt wind turbines at water depths below 10 m. In the past few years many offshore wind farms were erected. These projects are listed in Table 1.1. The plans for the near future are for wind farms with capacity in the order of many hundreds megawatt (or even gigawatt) that employ multi-megawatt machines at sites as far as 100 km from the shore and in water depths up to 40 m.

1.6 The DOWNVInD Project

One of the largest European research projects in the field of large scale offshore wind farms is the "DOWNVInD" project (Distant Offshore Windfarms with No Visual Impact in Deepwater). The project is a cooperation of European Universities, Agencies and private companies and is funded by the private sector as well as the EU. The project aims to understand the impact of deepwater windfarms, prove the deepwater windfarm concept and share experiences across the industry.

For this reason two demonstration wind turbines (each of 5 MW rated power) will be installed in the Moray Firth (Scotland offshore) at a depth of 40 meters. They will be situated 24 km from the shore in the area where the Beatrice oil field exists with 4 offshore platforms. These two turbines will be first ones to be erected in such deep water and at such distance. The program begun in the summer of 2004, with the demonstration turbines planned for installation in 2005. Total project duration will be 54 months. For these five years of the project duration, test data and useful experience from these offshore conditions should be collected [1.9], [1.10]. If successful, the DOWNVInD demonstration project could be the precursor of large offshore wind farms around Europe.

1.7 Summary

Wind Power systems constitute a reliable form of energy production. The technology and industry surrounding wind power is fully developed and mature in order to move forward and construct large offshore windfarms in the size range of several hundreds MW. All these, in combination with the public and political support can lead to the desired result of exploiting the significant offshore wind potential and reducing the pollutant emissions not only in Europe but worldwide.

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2

Transmission Systems from Offshore Windfarms

2.1 Introduction

In this chapter the technological solutions for transmission from offshore windfarms will be presented. The different topologies and components are analyzed and a synopsis of the advantages and disadvantages of each system is given. The analysis includes the following three transmission technologies:

- HVAC: High Voltages AC transmission,
- HVDC LCC: High voltage DC transmission with the use of Line Commutated Converters,
- HVDC VSC: High Voltage DC transmission with the use of Voltage Source Converters.

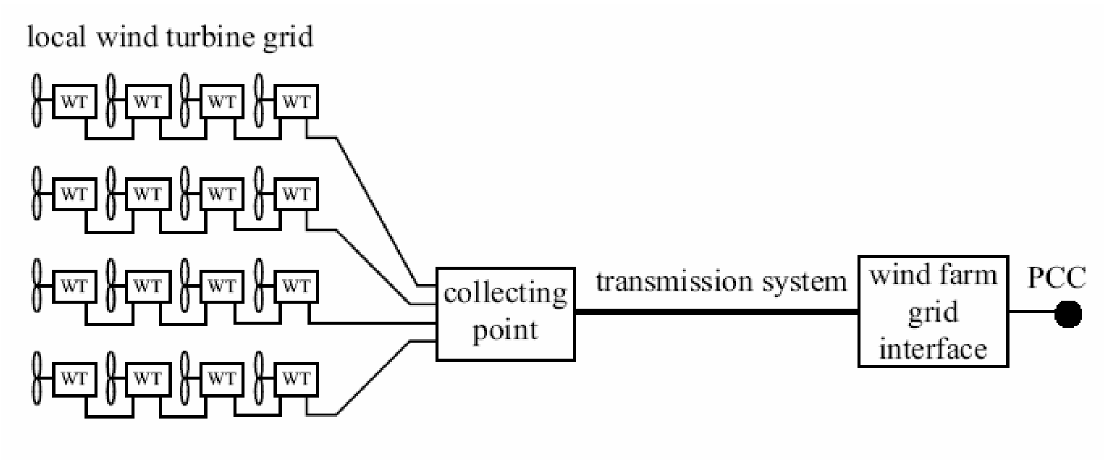


Figure 2.1: General layout of windfarm and transmission system (Lunberg [2.2])

2.2 HVAC Transmission

All commercial offshore windfarms until today use HVAC for the connection link to shore. A transmission system based on HVAC technology consists of the following main components:

- AC based collector system within the windfarm.

- Offshore transformer station that includes the transformer and the reactive compensators.
- Three core XLPE (cross linked polyethylene insulation) HVAC cable(s)
- Onshore transformer station and compensators

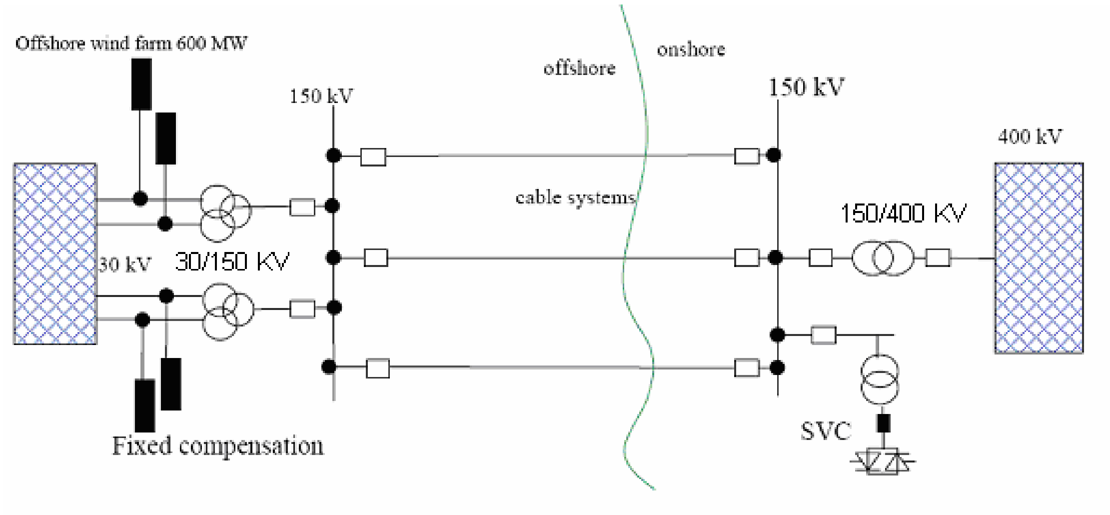


Figure 2.2: Configuration of an HVAC connection of a wind farm to the main grid [2.3]

In case of short distance transmission it is possible that neither the offshore transformer nor the offshore and onshore compensators will be necessary. The onshore transformer is needed when the transmission voltage is different than the voltage of the main grid onshore.

2.2.1 AC cables and Compensators

The main type of cables used for bulk power transmission with HVAC is the XLPE cable. XLPE cables have great continuous and short circuit current carrying capacity, resulting from their excellent thermal characteristics. They can be loaded continuously to a conductor temperature of 90^{o} C. The dielectric losses of a XLPE cable are significantly lower than other technologies (i.e. EPR cables) and since they require no oil supply system they are environmental friendly, require less maintenance and they are easier to install. According to ABB [2.4], three core submarine XLPE cables can be constructed today for voltages up to 245 kV with a power rating of 500 MW.

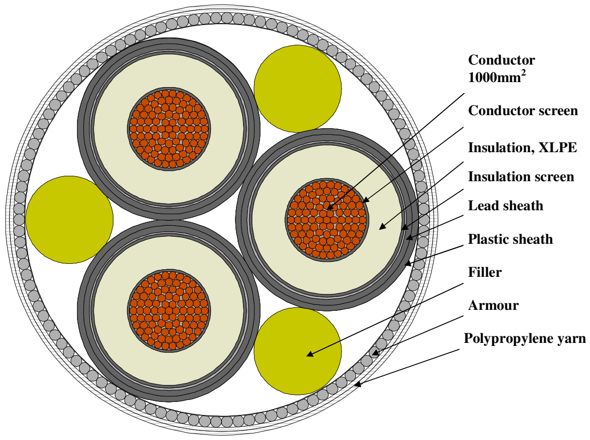


Figure 2.3: XLPE cable cross-section (Nexans Norway AS)

Generally cables have larger capacitance than overhead lines, thus when AC voltage is applied to it large amounts of reactive currents are generated throughout its length. This phenomenon decreases the ability of the cable to transmit active power especially at large distances. In order to provide more "space" for active current, the reactive current has to be distributed evenly at both cable ends. Different types of compensation topologies can be used to achieve that (VSC, capacitor banks etc).The data that are used in this work were acquired by the study of systems having Thyristor Controlled Reactor (TCR), installed both at the offshore and on shore cable ends in the role of compensators (for a detailed analysis of the calculation of reactive currents and the amount of compensation needed see [2.1]).

2.2.2 Transformers and Transformer Substations

If the transmission voltage is greater than 33 kV offshore transformer(s) are required to raise the voltage to the desired level. As for the onshore transformers they are required when the voltage of the transmission differs to the voltage of the main grid.

In order to house the offshore transformer and compensator, offshore substations will have to be built. These substations (offshore platforms) are rather large, complex and very costly constructions. The platform has to be designed in such a way that not only it will provide space for all the equipment to be installed but also will facilitate the proximity to these components in case of maintenance. It is also essential, for safety reasons, to include life support components.

Figure 2.4: The Nysted offshore transformer Substation

Figure 2.5: The Horns Rev offshore transformer Substation

Two cases of offshore transformer substations exist today: The Horns Rev and the Nysted offshore substation (both in Danish offshore projects). The Horns Rev platform is designed as a tripod construction, compared to the Nysted platform which is based on a monopile construction (Figures 2.4 and 2.5). The Horns Rev substation includes a steel building with a surface area of approximately 20x28 metres and is placed about 14 m above mean sea level. The platform accommodates among others the following installations [2.5].

- 36 kV switch gear
- 36/150 kV transformer
- 150 kV switch gear
- control and instrumentation system, as well as communication unit
- emergency diesel generator, including 2x50 tonnes of fuel
- sea water-based fire extinguishing equipment
- staff and service facilities
- helipad
- crawler crane
- MOB (man over board) boat

For large scale offshore windfarms (up to 1000 MW) it is likely that more than one offshore substation will be needed. The specifications of the DOWNVInD project suggest that the offshore substation will sited at areas with water depth of 40-50 m, raising the cost of construction to even higher levels. It should be noticed that the

Horns Rev windfarm is located at an area where the sea depth is 6-12 meters while the sea depth at the Nysted windfarm is 5-9.5 meters.

2.3 HVDC LCC

HVDC LCC has been used for bulk power transmission for many decades. The first commercial HVDC transmission system was installed in 1954 between the island of Gotland and mainland Sweden. Today many HVDC LCC links exist throughout the world, many of which involve submarine cables. Nevertheless, there has never been an HVDC LCC link that employs converters on offshore substations. An LCC transmission system consists mainly of the following components [2.6]:

- AC filters
- DC filters
- Converter transformer
- Thyristor valves
- Smoothing reactor
- STATCOM or capacitor banks
- DC cable and return path
- Auxiliary power set (i.e. Diesel generator)

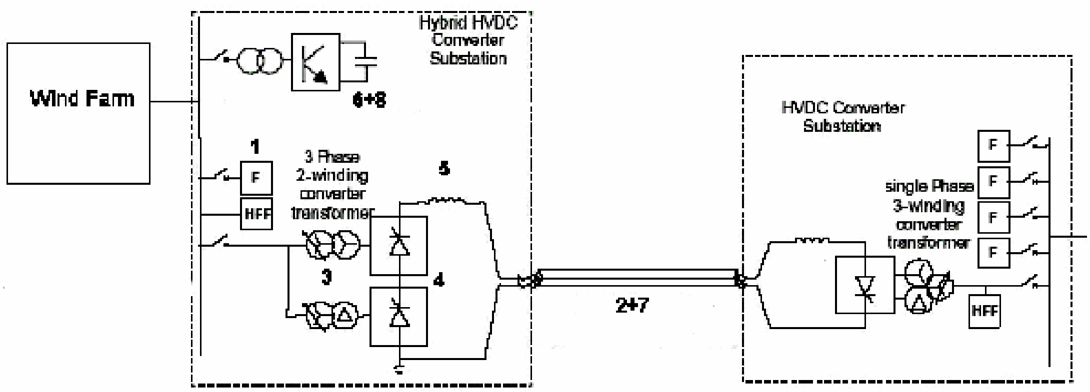


Figure 2.6: Configuration of a wind farm using LCC HVDC transmission system [2.7]. (1: AC filters, 2: DC filters, 3: Converter transformer, 4: Thyristor valves, 5: Smoothing reactor, 6: STATCOM or capacitor bank, 7: DC cable and return path, 8: Auxiliary power set)

2.3.1 Filters

AC filters are used in order to absorb harmonic currents generated by the HVDC converter and thus to reduce the impact of the harmonics on the connected AC system. AC filters also supply reactive power to the converter station.

DC filters are used to avoid that the harmonic voltage in the DC side will cause an AC current superimposed on the DC current in the transmission line.

2.3.2 Converter Transformer

In LCC transmission systems two converter transformers are required (one offshore and one onshore). Their configuration, as it can be seen from Figure 2.6, is to have the secondary offshore and the primary onshore with one star and one delta connection. This way several harmonics are cancelled and a significant reduction of filters is achieved. The overall design of a converter transformer for HVDC LCC transmission is more complicated than it is for ordinary transformers. The insulation has to withstand the AC component of the voltage plus the DC component coming from the thyristor valves.

2.3.3 Thyristor Valves

The thyristor valves are the most important component in the converter station, since they operate the conversion from AC to DC and vice versa. (for details about the topology of the valves within the converter see [2.6]). The available technology today gives thyristors characterized by silicon wafer of diameter up to 125 mm, blocking voltages up to 8 kV and current carrying capacities up to 4kV DC. With these characteristics it is possible to convert up to 1000 MW for land connections and up to 500 MW for submarine transmissions. In order to operate the thyristor valves require reactive power. For this reason filters and capacitor banks are used, but the usage of STATCOMs is also considered.

2.3.4 Smoothing Reactors

Smoothing reactors are large inductances connected in series with each pole. They prevent the current interruption at minimum load, limit the DC fault current, prevent resonances in the DC circuit and reduce the harmonic current caused by interferences from the overhead lines.

2.3.5 Capacitor Banks and STATCOMs

Since the valves in the converters require reactive power, it is necessary to include in the design of the converter station capacitor banks or STATCOMs. This way the control of the reactive power balance is achieved. Capacitor banks consist of a series of capacitors connected in parallel to the transformer. STATCOMs are designed with VSC technology and they improve the operation of the whole converter station due to their function to generate or consume reactive power.

2.3.6 DC Cables and Return Path

Two cables technologies have been developed until now [2.6]:

- Mass-impregnated cables
- Oil-filled cables

Mass-impregnated cables (MI) consist of a conductor, built on stranding copper layers on segments around a central circular rod, and oil and resin-impregnated papers which cover the conductor; the inner layers are of carbon-loaded papers and the outer layers is made of copper-woven fabrics. The cables is then covered with sheaths, jackets, anti-corrosion protections and armours in order to protect the cable from the environmental. The available technology for these cables is for voltages up to 500 kV and transmission capacity up to 800 MW for monopole solution, but 600 kV and 1000 MW solutions are under development. These cables can be installed at sea depths up to 1000 m under the sea level and with nearly unlimited transmission length. The capacity of this system is limited by the conductor temperature, which can reduce overload capabilities.

Oil-filled cables (OF) are insulated with paper impregnated with a low-viscosity oil under an overpressure of some bars and incorporated in a longitudinal duct to permit oil flow along the cable. These cables have been developed later compared with the previous type and the available technology today ensures voltages up to 600 kV and capabilities up to 1000 MW for monopole solution for land installation. Problems of this cable regard the length, since, due to the required oil flow along the cable, the cable length is limited to 100 km. Besides, the risk of oil leakage must be taken into account for environmental issues.

Some other solutions are under development: one considering a cross-linked polyethylene insulator (XLPE) that ensures high temperature of working during the transmission, and one using a lapped non-impregnated thin PP film insulator that should ensure very long and deep submarine installation due to the increase of the electrical stresses in operation.

For the return path of the current, earth electrode, metallic return conductor as a part of the DC cable or an AC cable with low voltage level can be chosen. The choice of one of the solution above depends on environmental conditions and restrictions of the site where the cable has to be installed. For example some problems can be present if the site is a natural park and thus an earth electrode is not suitable for the return path purposes.

2.3.7 Auxiliary Power Set

The purpose of the auxiliary power set is to supply power to the valves when they are fired at the beginning of the transmission. It also provides power to the cooling, control and protection devices when the wind farm is disconnected from the main grid.

2.3.8 Offshore Substation

As it has been mentioned before, there has never been a construction of an offshore platform to host a LCC converter and all of its components. It is important to notice that the overall size of a converter station using LCC technology is several times the size of a transformer station (used in HVAC transmission schemes). Thus, the size and apparently the cost of an offshore platform for HVDC LCC converter will be significantly bigger.

2.4 HVDC VSC

HVDC transmission based on VSC devices is a relatively new technology, since it has been developed after the evolution of IGBTs (Insulated Gate Bipolar Transistors). Commercially, HVDC VSC is promoted as HVDC light by ABB and as HVDC plus by Siemens. The first system was installed by ABB in Hellsjön, Sweden in 1997. It was a small transmission system (3 MW at 10 kV), installed mainly to test the reliability of the technology. Since then many HVDC VSC links have been constructed throughout the world (Table 2.1), some of which include submarine

	Name of the Project	Location		Year	Kind of interconnection	Power Rating	AC voltage [kV]	DC voltage [kV]	DC current [A]	Number of cable	Length of cable [km]	Converters		
		From	To									Number/ each end	Rated power each one	Switching frequency [Hz]
ABB Manufacture	Hellsjön - SWE	Hellsjön	Grängesberg	1997	Land connection	3 MW	50/50	+/- 10	150	2	10	1	3 MW	NA
	Gotland - SWE	Gotland	Gotland	1999	Underground connection	50 MW	80/80	+/- 80	350	2	70	1	50 MW	NA
	DirectLink - AUS	South Wales	Queensland	2000	Underground connection	180 MVA	132/110	+/- 80	342	6	59	3	65 MVA	NA
	Eagle Pass - USA	Eagle Pass	Eagle Pass	2000	Back-to-Back installation	36 MW	132/132	+/-15,9	1100	0	0	1	36 MW	NA
	Tjaereborg - DK	Tjaereborg	Tjaereborg	2000	Land connection for wind power transmission	8 MVA 7,2 MW	10,5/10,5	+/- 9	358	2	4,3	1	7,2 MW	1950
	Murray Link - AUS	Riverland	Victoria	2002	Underground connection	220 MW	132/220	+/- 150	739	2	180	1	220 MW	1350
	Cross Sound - USA	Connecticut	Long Island	2002	Submarine connection	330 MW	345/138	+/- 150	1175	2	40	1	350 MW	1260
	Troll A - NOR	Statoil Station	Kollnes	2005 (*)	Submarine connection	84 MW	56/132	+/- 60	350	4	70	2	42 MW	NA

List of Symbols		
	SWE	Sweden
	AUS	Australia
	USA	United State of America
	DK	Denmark
	NOR	Norway
	NA	Not Available

(*): under construction

Table 2.1: Existing HVDC VSC transmission systems (sourse [2.6])

cables. It is important to notice that, as in HVDC LCC, never a VSC converter has been built offshore.

A basic configuration of a transmission link from an offshore windfarm using HVDC VSC technology can be seen in Figure 2.7.

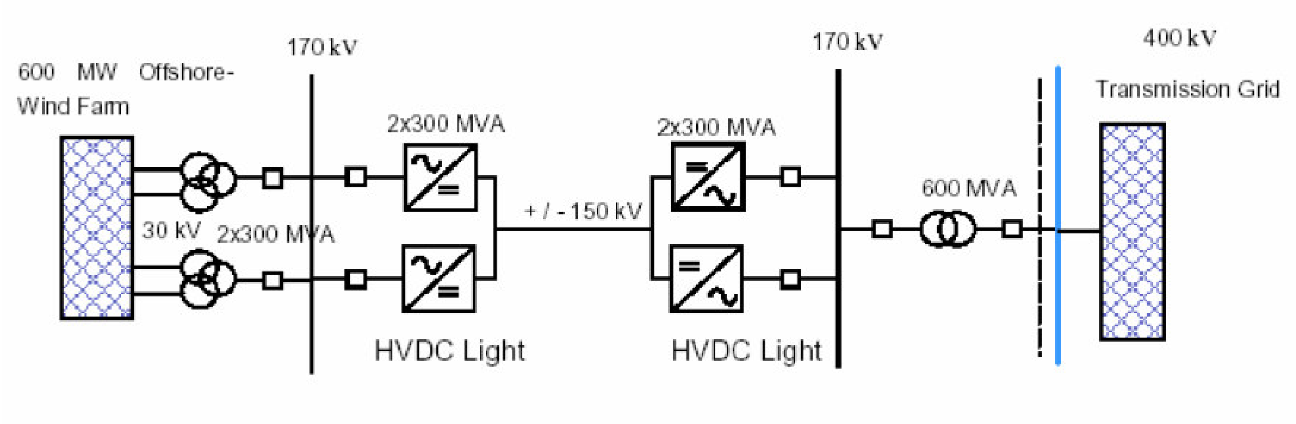


Figure 2.7: Basic configuration of a HVDC VSC transmission line from an offshore windfarm [2.8]

The main components of an HVDC VSC based transmission for offshore wind farms line are:

- Converter stations (both offshore and onshore)
- Cable pair (polymeric extruded cables)

HVDC VSC configurations are capturing more and more attention due to some expected advantages, which extend the possibility of uses of this system.

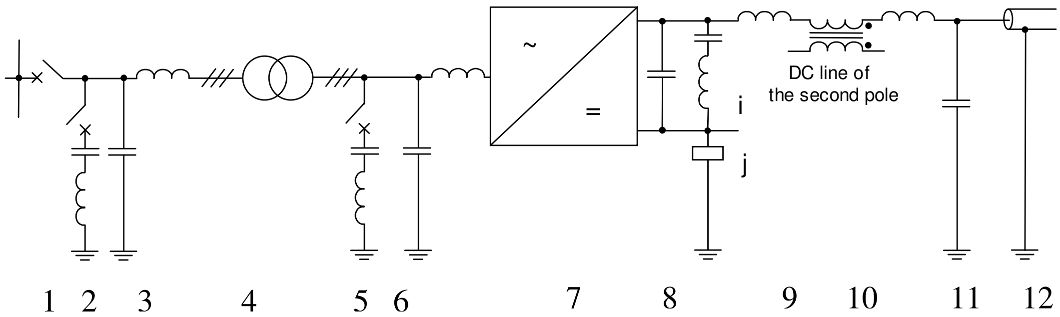
- Independent control of active and reactive power in each converter station. This allows controlling the transmitted power in the system. In the offshore station reactive power can be generated to supply wind turbines and the injection of active power in the transmission system can be control. In the onshore station, reactive and active power can be varied in order to control voltage and frequency variations in the AC network. In other words the system can operate in all four quadrants of the PQ-plane.
- Connection of the system to a weak AC grid since active and reactive power can be controlled. A windfarm can create problems if it is connected to weak grids due to the variations of the wind and the produced power. These problems can be solved when the control of active and reactive power is achieved.
- No risk of commutation failure as in LCC systems

- Decoupling of the connected AC networks.
- Possible function as a STATCOM supplying or consuming reactive power without absorption or generation of active power. This feature can be useful if the voltage level must be controlled at one end of the transmission system for stability reasons.
- Easier implementation of multiterminal schemes since the polarity on the DC side is the same in both the inverter and rectifier mode.
- The system is easier to design and more compact than a LCC station since fewer components are required. There is no need for STATCOMs or capacitor banks and fewer filters are installed in VSC converters. For this reason the size of the offshore platform that will be required to host the VSC converter station is smaller compared to LCC solutions.

2.4.1 HVDC VSC Converter Station

The principle scheme of a VSC system converter station is shown in Figure 2.8 including a list of its main components [2.6]. The most important component of the converter station is the VSC unit. It is in this unit where the AC to DC (and vice versa) conversion takes place. The device is based on IGBT components and it can reach high levels of converted power due to evolution of this semiconductor type. The switching frequency of the converter is of great importance. High value of switching frequency can reduce the number of harmonics and thus the number of filters but it increases the power losses and the inefficiency of the system. Existing VSC HVDC systems are designed with switching frequency between 1300 Hz (Cross Sound Cable) and 2000 Hz (Tjaereborg with wind power transmission).

A transformer connects the AC system to the converter in order to step up the voltage level for conversion in the VSC device. The interface transformer also provides reactance between the AC system and VSC system and prevents zero frequency currents from flowing between the AC system and the converter.



1) VSC converter station circuit breaker
2) System side harmonic filter
3) AC side Radio Frequency Interference filter
4) Interface transformer
5) Converter side harmonic filter
6) HF-blocking filter/phase reactor
filter [b)]
7) VSC unit
line[b)]

8) VSC dc capacitor
9) DC harmonic filter
10) Neutral point grounding branch[a)]
11) DC reactor [b)]
12) Common mode blocking reactor [b)]
13) DC side Radio Frequency Interference
14) DC cable or overhead transmission

[a)] The location of the neutral point grounding branch may be different depending on the design of the VSC unit.
[b)] Not normally applicable for Back-to-Back systems.

Figure 2.8: Main components of a VSC Substation [2.6]

A number of filters are used both on the DC and AC side. These filters are mainly used to decrease the influence of harmonics induced in the system and to improve the overall performance of the converter (for detailed analysis see [2.6]).

The presence of auxiliary power equipment is necessary in the offshore converter substation in order to provide power to some components (cooling system, air conditioning system, control and protection devices), when the windfarm is disconnected.

2.4.2 DC Cables

The cables used in VSC transmission systems are based on the extruded polymeric insulation technology. This solution has better thermal characteristics compared oil filled or mass impregnated cables. It also requires less auxiliary components and its maintenance is much simpler. Extruded cable presents good mechanical flexibility and strength and it can be installed also at high depth in submarine applications.

2.5 Summary of Advantages and Disadvantages of Transmission Systems

A more thorough analysis of specific transmission systems of all three technologies will be presented in the chapters to follow. The analysis of the systems will be economical, based on cost models that will have the losses and the energy availability as parameters. All this parameters will be discussed extensively. However, it is considered important to summarize some of the special features of each transmission technology in order to provide an overall view of their technical characteristics.

It is interesting to notice that even though all of the existing offshore windfarms use HVAC transmission system, the available technology limits their power transmission capability. Nonetheless, three core XLPE cables with voltage rating up to 400 kV are under development which will allow power up to 800 MW to be transmitted at distances of 100 km [2.1]. The transmission capability of HVAC system reduces with distance because of the dielectric losses and the reactive power that is produced along the cable. HVDC transmission systems, such as LCC and VSC, don't have a distance dependent power transmission capability and with the existing technology can be rated up to 600 MW and 500 MW respectively for submarine applications (in a single pole configuration). However, HVDC systems have never been installed in offshore applications and will require massive offshore infrastructure (offshore platforms) in order to do so.

A great advantage that HVDC systems provide is the decoupling of the connected AC networks. Faults and frequency variations in the onshore main grid do not affect the network within the windfarm and vice versa. Furthermore, HVDC VSC can be connected in weak grids since it has excellent network support features. By choosing HVDC VSC technology there is no need to upgrade the onshore network, resulting in a significant lower overall cost. Another interesting feature that HVDC VSC provides (also provided by HVAC systems) is its "black start" capability, meaning that it can power up networks that have suffered 100 percent failure.

When the power output from the windfarm is low HVDC systems require auxiliary systems in order to provide power in some of their components (cooling system, air conditioning system, control and protection devices). Auxiliary power systems are not necessary in HVAC transmission systems.

It is obvious that depending on the requirements of an offshore windfarm project (transmission distance, installed capacity, necessity to upgrade or not the grid etc) one of the three transmission technologies can be chosen with respect to their special features. It would be irrational to exclude one of the systems as a bulk power transmission solution without a detailed analysis of the characteristics of every different windfarm project.

2.6 References and Sources

[2.1] Todorovic J.,"Losses Evaluation of HVAC Connection for Large Offshore Wind Farms", Masters Thesis, Department of Electrical Engineering, Royal Institute of Technology, Stockholm, Sweden, 2004

[2.2] Lundberg S., "Configuration Study of Large Wind Parks", Licentiate thesis, Chalmers University of Technology, School of Electrical and Computer Engineering, Göteborg, Sweden, 2003

[2.3] Eriksson K., Wensky D., "System Approach on Designing an Offshore Windpower Grid Connection", Fourth International Workshop on Large-Scale Integration of Wind Power and Transmission Networks for Offshore Wind Farms, Billund, Denmark, October 20-21, 2003

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[2.7] Cartwright P., Xu L., Sasse C., "Grid Integration of Large Offshore Wind Farm Using Hybrid HVDC Transmission", Nordic Wind Power Conference, Chalmers University of Technology, Göteborg, 2004

[2.8] Wright S. D., Rogers A. L., Manwell J. F., Ellis A., "Transmission Options For Offshore Wind Farms in the United States", Renewable Energy Research Lab University of Massachusetts, AWEA 2002

3

Wind Speed Distribution and Wind Farm Model

3.1 Introduction

As it was mentioned before the purpose of this study is to make an economical evaluation of several transmission systems from offshore windfarms. The cost of the components that each transmission system includes, their losses and their energy availability are input parameters to this analysis. In order to evaluate the losses of a transmission system the input power to the system, thus the output power from the windfarm has to be known. However, windfarms are not ordinary power plants. Even though their driving force, the wind, is free of charge, their power production cannot follow an increase of the consumption. In this chapter the model used to define the output power of a windfarm is presented. The approach has been based on Holttinnne and Norgaard [3.1] and was developed by Todorovic [3.2] and Barberis [3.3].

3.2 Aggregated Power Curve for a Wind Farm

In order to model the output power of a wind farm, an aggregated model is used. This methodology follows the multi-turbine power curve approach presented by Holttinne and Norgaard in [3.1] and it allows to generate a good estimation of the wind farm output power that can be used for further analyses of losses and reliability.
The model is based on one wind speed distribution, a standard 5 MW wind turbine power curve, the dimension (front side size respect to the wind direction) of the area where the wind farm is placed and the wind turbulences intensity. All this parameters are the input data of the model.

3.2.1 Wind Speed Probability Distribution

The wind speed can be treated as a continuous random variable. The probability that a wind speed shall occur can be described with a density function

[3.4]. The one used here is the Rayleigh distribution which is expressed by Equation 3.1:

$$f(w_s) = \frac{k}{c}\left(\frac{w_s}{c}\right)^{k-1} e^{-\left(\frac{w_s}{c}\right)^k} \qquad \text{Eq. 3.1}$$

where

$f(w_s)$ = probability density

w_s = wind speed [m/s]

k = shape parameter = 2

c = scale parameter = $\frac{2}{\sqrt{\pi}} w_{s,avg}$

$w_{s,avg}$ = average wind speed in the area equal to 8, 9, 10 or 11 m/s

In Figure 3.1 Rayleigh distributions for different average wind speeds in the area are shown. It is possible to notice that increasing the average wind speed, the peak of the distribution decreases, but the width of the curve increases.

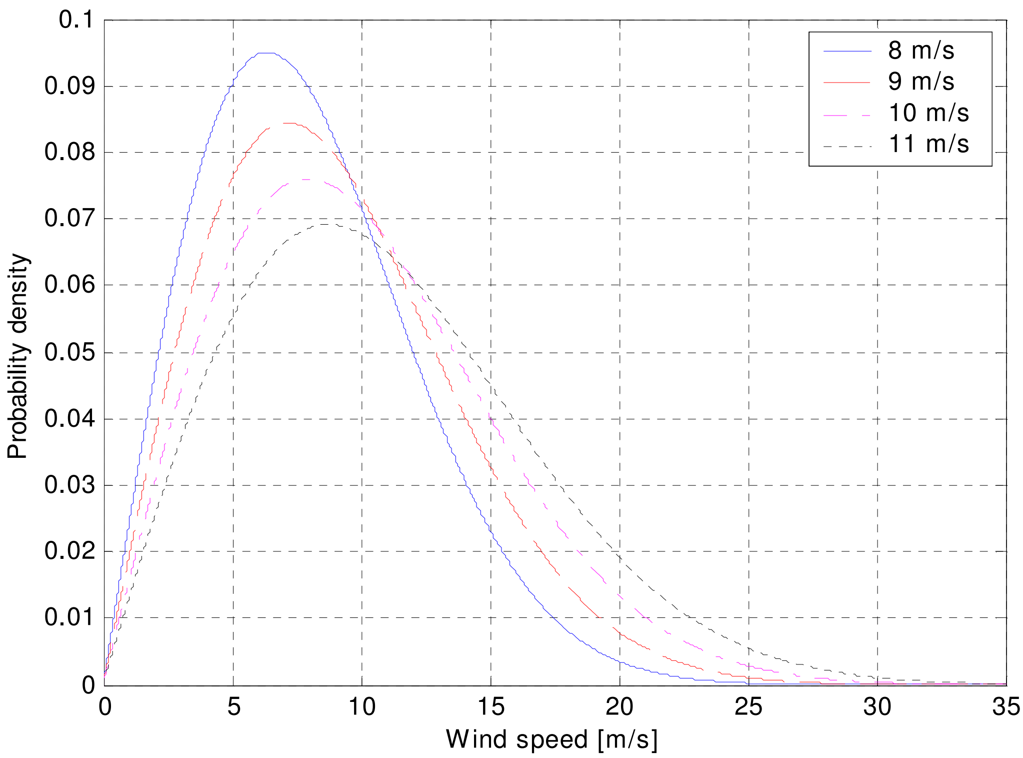

Figure 3.1: Rayleigh distribution for different average wind speeds

3.2.2 Dimension of the Windfarm Area and Wind Turbulence Intensity

The dimension D of the windfarm area depends on the installed rated capacity of the windfarm and its layout. This dimension D represents the length of the side of the windfarm that is perpendicular to the direction of the wind. If the distance between two neighbouring towers is considered to be nine time the diameter of the rotor (127 m) this is translated to almost 1 km. Thus, for a wind farm of 400 MW settled in five rows D will be approximately 20 km. Having always the same layout of the windfarm (5 rows), an increase of 100 MW in the rated power will lead to an increase of 5 km in D. For 1000 MW windfarm the dimension D will be 50 km (Figure 3.2)

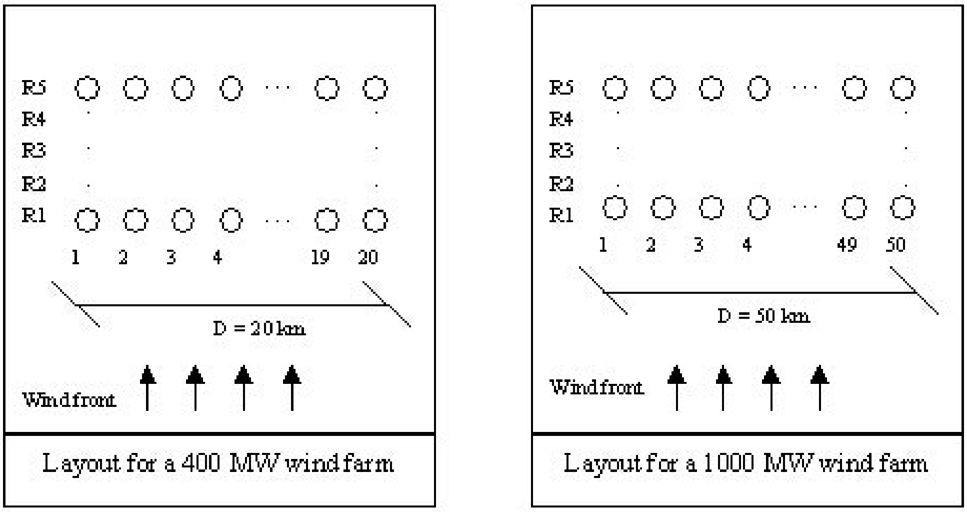

Figure 3.2: Dimension D of two different windfarm. [3.3]

For the wind Turbulence intensity a value of 10% was chosen considering that in an offshore environment the turbulences are relatively smaller.

3.2.3 Wind Turbine Power Curve

As it was mentioned the chosen wind turbine is rated at 5 MW. The power curve of a single turbine is shown in Figure 3.3. The cut in and cut out speed of the turbine are 3.5 m/sec and 30 m/sec respectively, the rotor diameter 126 m and air density is considered to be 1.125 kg/m^3. It is assumed that all the turbines are equal in size, uniformly distributed and have the same power curve.

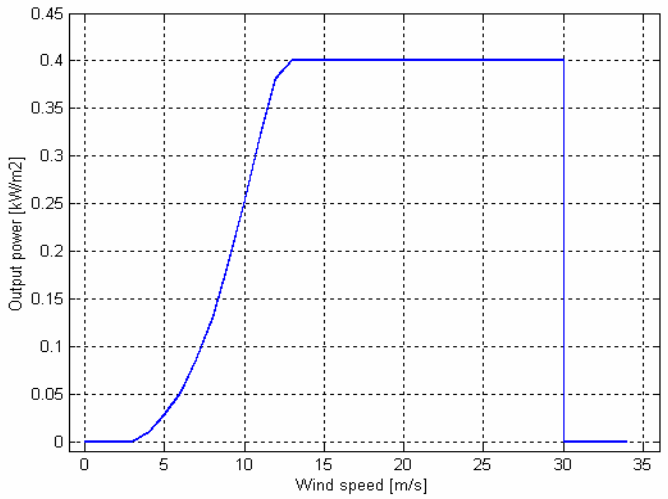

Figure 3.3: Output power curve for a single 5MW wind turbine. The swept area of the blades is assumed equal to the total area swept by the blades (A = 12469 m2) [3.2].

3.2.4 Methodology

Windfarms, especially the ones with installed capacity of several hundreds MW extend over a large area. It is not possible to assume that at a given time the wind has the same speed throughout the entire area of the farm and thus in front of all the wind turbines. So for a given mean value of wind speed the actual speed of the wind in different locations within the windfarm will deviate, depending on D and I. In order to describe the probability that the wind speed will differ from the mean wind speed at a given time, a probability function is produced. The parameters that influence this distribution function are: the value of the mean wind speed, the dimension D of the windfarm and the level of turbulences (for detailed analysis see [3.1]). An example of such a distribution is shown in Figure 3.4.

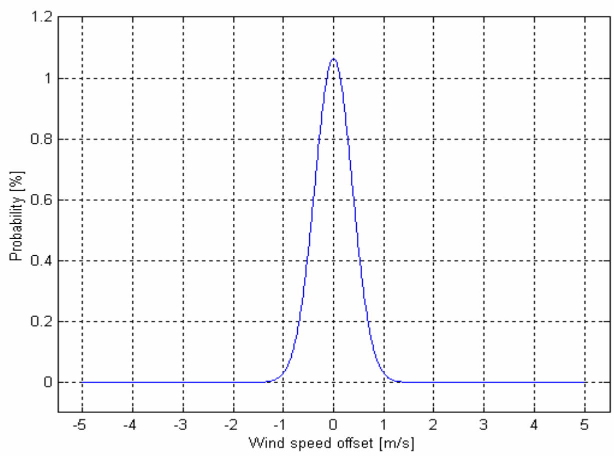

Figure 3.4: Probability distribution function with $w_{s,avg}$ = 9 m/s, D = 25 km, I = 10% [3.3]

If the distribution of the wind speed around the block average values (showed in Figure 3.4) is applied on the power curve representative for a single unit, a smoothed multi-turbine power curve that is representative for the aggregated power output for the wind turbines within the area will be obtained (Figure 3.5).

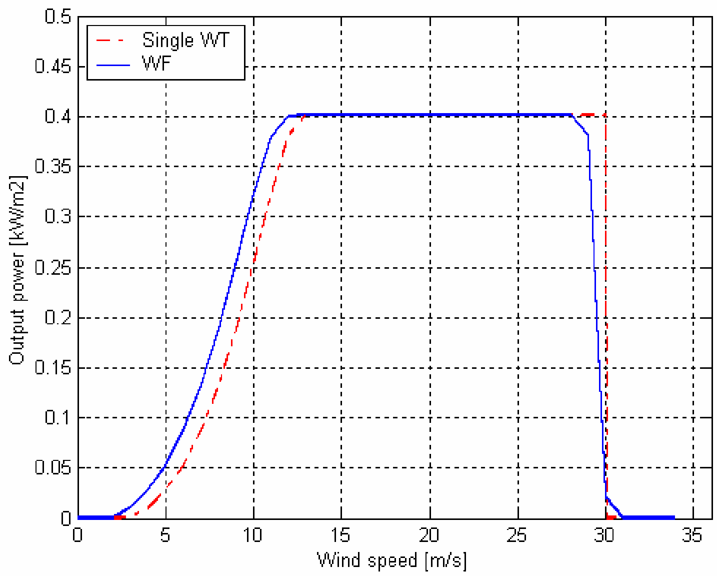

Figure 3.5: Comparison between the single-machine power curve and then multi-machine power curve for a 500 MW wind farm and an average wind speed in the area of 9 m/s [3.3].

In order to represent the aggregated power curve for the whole wind farm, it is necessary to multiple the obtained power curve to the swept area and the number of installed wind turbines. The curve is shown in Figure 3.6 for two sizes of wind farm (500 MW and 1000 MW) and the same average wind speed in the area (9 m/s).

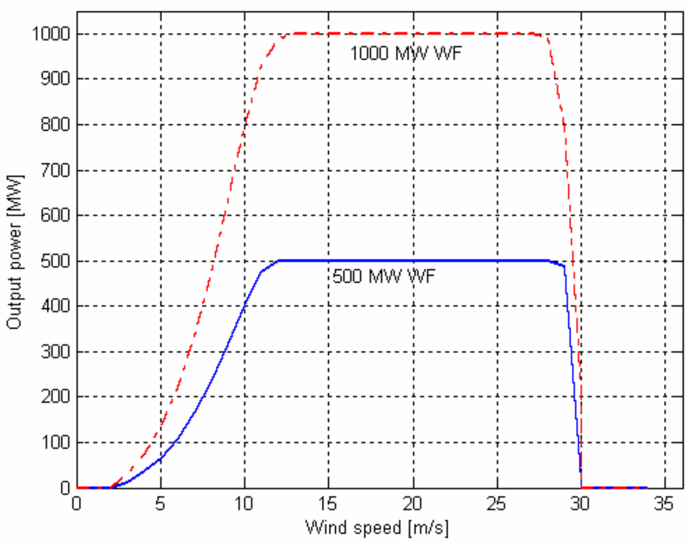

Figure3.6: Aggregated power curve for 500 MW and 1000 MW wind farm (WF) with 9 m/s average wind speed in the area [3.3]

The cut in and cut out wind speeds for the entire windfarm are 2 m/s and 31 m/s respectively. This deviation from the cut in and cut out speed of a single turbine is reasonable, considering the fact that the actual wind speed varies around the mean value. In some locations within the windfarm the wind speed will be above the cut in speed of a single turbine, even if the mean wind speed is bellow that value. Thus the energy production begins at speeds bellow 3.5 m/s. The same phenomenon can explain why the cut out speed of the windfarm is larger than the one of a single turbine.

Using the aggregated power curve and the assumed wind speed distribution in the area (Rayleigh distribution), it is possible to calculate the power output of the wind farm. The power curves that were obtained for the different ratings of the windfarm were used by Todorovic [3.2] and Barberis [3.3] for the calculations of the losses in the transmission lines. They are also going to be used for the calculations of the energy availability of several transmission systems in this work. In the figure bellow the duration curve for a 500 MW windfarm is presented. This curve is the result of the of the method described above, namely the combination of the aggregated power curve for a 500 MW windfarm with the Rayleigh distribution for 8, 9, 10 and 11 m/s.

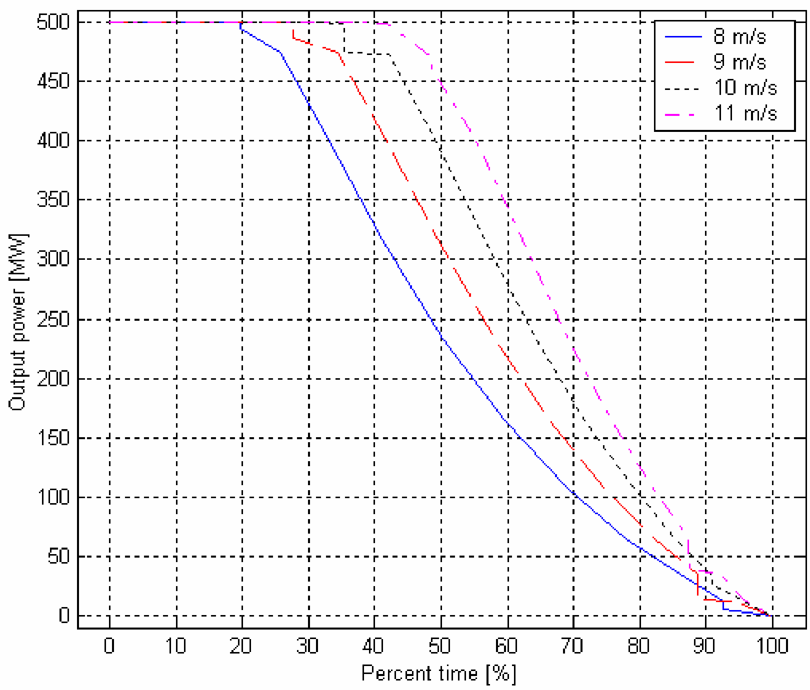

Figure 3.7: Duration curve for a 500 MW wind farm with different average wind speeds in the area [3.3]

It is also possible to calculate the average power output from the wind farm as described bellow:

$$\mathrm{P_{avg}} = \int_{w_{sin}}^{w_{sout}} P(w) \cdot f(w) dw \qquad \text{Eq 3.2}$$

where:

w =The wind speed

$f(w)$ =The Rayleigh probability distribution

$P(w)$ =The power output from the windfarm according to the aggregated model

$w_{\sin}$ =The cut in speed

w_{sout} =The cut out speed

The results for the several windfarm sizes and average wind speeds used in this work are shown in Table 3.1

Average Wind Speed [m/s] / Wind Farm Rated Power [MW]	8	9	10	11
400	190.70	219.66	243.68	262.81
500	238.40	274.58	304.56	328.44
600	286.11	329.50	365.42	394.00
700	333.88	384.42	426.24	459.54
800	381.63	439.33	487.10	525.11
900	429.38	494.25	547.94	590.65
1000	477.20	549.16	608.71	656.06

Table 3.1: Average output Power from the windfarm in MW varying the size of the rated power and the average wind speed.

In order to calculate the energy produced in a given period for each case, the average power output is multiplied to the duration (hours) of the given period. I order to have realistic results the chosen period should be chosen large enough to include all seasonal wind speed variations. The energy produced from the wind farm for a period of one year is presented in Table 3.2.

Average Wind Speed [m/s] / Wind Farm Power [MW]	8	9	10	11
400	1.67	1.92	2.13	2.30
500	2.08	2.40	2.66	2.87
600	2.50	2.88	3.20	3.45
700	2.92	3.36	3.73	4.02
800	3.34	3.84	4.26	4.60
900	3.76	4.32	4.80	5.17
1000	4.18	4.81	5.33	5.74

Table 3.2: Annual Output Energy of the wind farm in TWh varying wind speed and size of the wind farm during one year with 100% availability [3.3]

3.3 Summary

In order to represent a large number of wind turbines distributed onto a wide offshore area, the aggregated windfarm power model is required. The distribution of the wind speed can be described by the Rayleigh function. Following the method described by Norgaard and Holttinen [3.1] the power curve for the entire windfarm can be obtained. The aggregated power curve has a smoother shape compared to the power curve of a single turbine, mainly due to the fact that the actual wind speed can deviate around the average value within the extended area of an offshore windfarm. The aggregated power curve is simulating the windfarm and is used as input to the transmission systems for the evaluation of their losses and energy unavailability.

3.4 References and Sources

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4

Presentation of the Transmission Systems of Study and their Losses

4.1 Introduction

In order to make an economical evaluation of transmission systems several transmission schemes were chosen to be studied. These transmission schemes include all three technologies: HVAC, HVDC LCC and HVDC VSC. They are exactly the same used by Todorovic [4.1] and Barberis [4.2] in their study of the losses evaluation from large offshore windfarms. In this chapter the choices of transmission systems made by Todorovic and Barberis will be described with respect to their components and their characteristics (number and type of cables, rated power of transformers, compensators and converter stations etc). The configurations of the transmission systems are very important for the calculation of the energy availability and evaluation of the total investment cost for each scheme. Also the losses of each transmission system are presented in this Chapter.

4.2 HVAC Transmission Schemes

In his study, Todorovic [4.1] uses three levels of transmission voltage: 132 kV, 220 kV and 400 kV. Three types of HVAC cables are being considered:

- For 132 kV transmission systems: three-core TKVA 145 kV 3x1x1000 mm^2 KQ. The cable is XLPE insulated and has a nominal current of 1055 A.
- For 220 kV transmission systems: three-core cable TKVA 245 kV 3x1x1000 mm^2 KQ. The cable is XLPE insulated and has a nominal current of 1055 A.
- For 400 kV transmission systems: three single core XLPE 400 kV cables in trefoil formation. The cross-section of the Cu of these cables is 1200 mm^2 and its nominal current 1323 A. This choice was made since the 400 kV, three-core XLPE, submarine cable is still under development and no data was available for it. In this study though, from now on, when referring to a 400 kV XLPE cable it is assumed that it is a three-core submarine cable.

In HVAC transmission systems, in order to provide more space for active current flow, the reactive current has to be distributed evenly at both ends of each cable. Todorovic uses Thyristor Controlled Reactors (TCR) to provide compensation. These compensators are placed at both sides of each cable. The amount of compensation needed in each case is calculated with the help of the MATLAB code provided by Todorovic [4.1] and it is presented in Table 4.2. The total number of compensators units used is twice as much the number of cables.

The number of cables that are required for the transmission of the power onshore depends on the rated power of the windfarm and the transmission distance. In Figure 4.1 the transmission capacity of the three cables mentioned before, is presented with respect to the transmission distance.

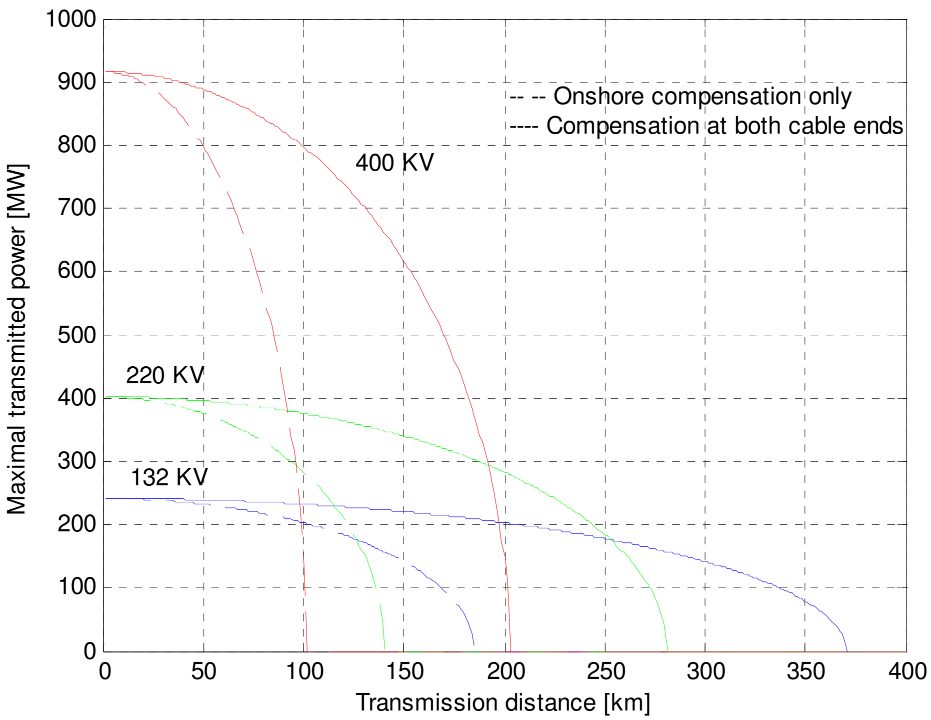

Figure 4.1: Limits of cables transmission capacity for three voltage levels, 132 KV, 220 KV and 400 KV; 1000 mm^2 Cu cross section and I_{nom} =1055 A for 132 KV and 220 KV; 1200 mm^2 Cu cross section and I_{nom}=1323 A for 400 KV voltage level, both compensation solutions, i.e. at each cable end and onshore only [4.1]

The voltage level of the grid within the windfarm is 33 kV while the voltage level of the onshore main grid is 400 kV. For this reason no onshore transformers are required when a transmission voltage of 400 kV is selected. All the HVAC transmission systems studied in [4.1] are summarized in Table 4.1.

	Transm. voltage	Offshore transformers	Onshore transformers	Number of cables required for each transmission distance					
				50 km	100 km	150 km	200 km	250 km	300 km
400 MW	132 kV	1x400 MVA	1x500 MVA	2	2	2	2	3	3
	220 kV	1x400 MVA	1x500 MVA	2	2	2	2	3	-
	400 kV	1x400 MVA	Not required	1	1	1	3	-	-
500 MW	132 kV	1x500 MVA	1x500 MVA	3	3	3	3	3	4
	220 kV	1x500 MVA	1x500 MVA	2	2	2	2	3	-
	400 kV	1x500 MVA	Not required	1	1	1	4	-	-
600 MW	132 kV	2x300 MVA	2x300 MVA	3	3	3	3	4	5
	220 kV	2x300 MVA	2x300 MVA	2	2	2	3	4	-
	400 kV	2x300 MVA	Not required	1	1	1	5	-	-
700 MW	132 kV	1x300+1x400 MVA	2x500 MVA	3	4	4	4	4	5
	220 kV	1x300+1x400 MVA	2x500 MVA	2	2	3	3	4	-
	400 kV	1x300+1x400 MVA	Not required	1	1	2	5	-	-
800 MW	132 kV	2x400 MVA	2x500 MVA	4	4	4	4	5	6
	220 kV	2x400 MVA	2x500 MVA	3	3	3	3	5	-
	400 kV	2x400 MVA	Not required	1	2	2	6	-	-
900 MW	132 kV	1x500+1x400 MVA	2x500 MVA	4	4	5	5	6	7
	220 kV	1x500+1x400 MVA	2x500 MVA	3	3	3	4	5	-
	400 kV	1x500+1x400 MVA	Not required	2	2	2	7	-	-
1000 MW	132 kV	2x300+400 MVA	2x500 MVA	5	5	5	5	6	8
	220 kV	2x300+400 MVA	2x500 MVA	3	3	3	4	6	-
	400 kV	2x300+400 MVA	Not required	2	2	2	7	-	-

Table 4.1: Description of the HVAC systems configuration used by Todorovic [4.1] for the losses calculations. The cables are three-core with XLPE insulation.

MVA	Transmission Distance					
Transmission Voltage	50 km	100 km	150 km	200 km	250 km	300 km
132 kV	32.5	65	97.5	130	162.5	195
220 kV	71	142	213	284	355	-
400 kV	226	452	678	904	-	-

Table 4.2: Compensation needed (MVA) at each end of each cable installed according to the voltage level and the transmission distance. No active power can be transmitted above 250 km for 220 kV cables and above 200 km for 400 kV cables.

As it is possible to notice from Figure 4.1 the 220 kV cable is not able to transmit any active power over 280 km and the 400 kV cable above 200 km. As a result of this, for transmission distances above the aforementioned ones, the corresponding blocks in Tables 4.1 and 4.2 are kept empty.

From Table 4.1 one can observe that in many cases the transmission systems, or some of their components, have rated power extremely higher than the required. For example, in the 700 MW windfarm cases, two 500 MVA onshore transformers where used which means that they are 300 MVA overrated. Todorovic [4.1] made this choice due to lack of technical data for transformers that would compose a transmission system at the exact rated power of the windfarm. This is also observed in many cases for the cables. As it can be seen from Figure 4.1, the 400 kV cable for 50 km of transmission length has a power transmission capability of almost 880 MW. Nevertheless this cable at this transmission length is often used for windfarms that have much smaller values of installed power production.

Choosing overrated components in a transmission system is often suggested in order to increase the reliability and to improve the overall performance. It is though not realistic to overrate a component this much. In this study, wherever it is possible, assumptions are made in order to have a more realistic approach. In some cases transformers with less rated power are used while it is assumed that the losses of the transmission system remain the same. It is not though possible to make the same assumption for the cables since a change in their characteristics will effect the entire losses model significantly (see [4.1]).

When the power transmission capability of a cable is exceeded, the model that Todorovic developed in MATLAB automatically adds one more in order to transmit the produced from the windfarm power, in some cases only for a few MW. These cases were detected and shall be presented separately. Small modifications in the MATLAB code provided by Todorovic [4.1] made possible instead of increasing the number of cables to decrease the rated power of the windfarm (reduce the number of turbines by a small number) and thus have a better rated system. In any case, all the changes and the assumptions made in this study, based on the layouts that are presented in Table 4.1, will be thoroughly described in order to be followed easily by the potential reader.

In Tables 4.3, 4.4 and 4.5 the average power losses of the HVAC transmission systems described in Table 4.1 are presented. The input to the transmission systems are windfarms with average output power given in Table 3.1. Detailed analysis of the losses calculations is given in [3.1].

%	**400 MW windfarm**											
	132 kV				220 kV				400 kV			
Length	8 m/s	9 m/s	10m/s	11m/s	8 m/s	9 m/s	10m/s	11m/s	8 m/s	9 m/s	10m/s	11m/s
50 km	2,67	2,73	2,78	2,81	1,63	1,61	1,59	1,57	1,19	1,13	1,10	1,07
100 km	5,13	5,26	5,36	5,43	2,92	2,87	2,83	2,81	2,85	2,64	2,51	2,43
150 km	8,13	8,30	8,44	8,54	4,97	4,85	4,77	4,71	5,93	5,40	5,07	4,84
200 km	11,98	12,17	12,32	12,45	7,86	7,62	7,47	7,38	18,47	17,54	16,93	16,52
250 km	14,28	14,12	14,03	13,97	13,55	13,08	12,78	12,59	-	-	-	-
300 km	20,39	20,11	19,95	19,85	-	-	-	-	-	-	-	-
%	**500 MW windfarm**											
	132 kV				220 kV				400 kV			
Length	8 m/s	9 m/s	10m/s	11m/s	8 m/s	9 m/s	10m/s	11m/s	8 m/s	9 m/s	10m/s	11m/s
50 km	2,81	2,78	2,76	2,74	1,62	1,63	1,64	1,65	1,18	1,14	1,12	1,11
100 km	4,74	4,77	4,79	4,81	3,07	3,07	3,07	3,07	2,68	2,54	2,46	2,40
150 km	7,50	7,53	7,56	7,57	5,10	5,05	5,02	5,01	5,36	4,98	4,74	4,58
200 km	11,08	11,09	11,10	11,10	7,87	7,76	7,69	7,65	18,29	17,59	17,15	16,85
250 km	15,28	15,30	15,33	15,37	12,48	12,12	11,89	11,74	-	-	-	-
300 km	19,96	19,74	19,61	19,53	-	-	-	-	-	-	-	-

Table 4.3: Average power losses in percent of the windfarm's average output power for different windfarm rated power, average wind speed, transmission distances and transmission voltage levels. Part One

%	600 MW windfarm											
	132 kV				220 kV				400 kV			
Length	8 m/s	9 m/s	10m/s	11m/s	8 m/s	9 m/s	10m/s	11m/s	8 m/s	9 m/s	10m/s	11m/s
50 km	2,83	2,86	2,89	2,91	1,89	1,90	1,91	1,92	1,23	1,21	1,20	1,19
100 km	5,39	5,47	5,53	5,58	3,31	3,35	3,39	3,42	2,68	2,58	2,52	2,49
150 km	8,45	8,57	8,66	8,73	5,38	5,41	5,44	5,47	5,14	4,85	4,68	4,57
200 km	12,31	12,45	12,55	12,64	7,64	7,49	7,51	7,44	17,17	16,80	16,60	16,49
250 km	14,60	14,57	14,55	14,55	12,53	12,23	12,04	11,92	-	-	-	-
300 km	19,79	19,58	19,57	19,47	-	-	-	-	-	-	-	-
%	700 MW windfarm											
	132 kV				220 kV				400 kV			
Length	8 m/s	9 m/s	10m/s	11m/s	8 m/s	9 m/s	10m/s	11m/s	8 m/s	9 m/s	10m/s	11m/s
50 km	3,32	3,37	3,42	3,45	1,94	1,98	2,02	2,04	1,26	1,25	1,25	1,26
100 km	5,54	5,69	5,48	5,45	3,67	3,74	3,80	3,85	2,70	2,65	2,62	2,61
150 km	7,96	7,99	8,00	8,01	5,19	5,12	5,06	5,02	4,85	4,62	4,48	4,39
200 km	11,20	11,25	11,30	11,34	7,66	7,57	7,51	7,48	16,64	16,03	15,63	15,35
250 km	15,53	15,61	15,69	15,76	11,93	11,69	11,53	11,43	-	-	-	-
300 km	20,04	19,94	19,90	19,88	-	-	-	-	-	-	-	-
%	800 MW windfarm											
	132 kV				220 kV				400 kV			
Length	8 m/s	9 m/s	10m/s	11m/s	8 m/s	9 m/s	10m/s	11m/s	8 m/s	9 m/s	10m/s	11m/s
50 km	2,88	2,90	2,92	2,94	1,85	1,84	1,83	1,90	1,31	1,33	1,34	1,36
100 km	5,52	5,59	5,63	5,67	3,17	3,34	3,33	3,32	2,55	2,47	2,40	2,36
150 km	8,66	8,75	8,82	8,87	5,16	5,15	5,15	5,15	4,63	4,43	4,31	4,23
200 km	12,15	12,31	12,44	12,54	7,79	7,75	7,74	7,74	16,23	15,85	15,61	15,45
250 km	15,13	15,12	15,11	15,11	11,84	11,66	11,55	11,48	-	-	-	-
300 km	19,78	19,68	19,63	19,60	-	-	-	-	-	-	-	-
%	900 MW windfarm											
	132 kV				220 kV				400 kV			
Length	8 m/s	9 m/s	10m/s	11m/s	8 m/s	9 m/s	10m/s	11m/s	8 m/s	9 m/s	10m/s	11m/s
50 km	3,16	3,22	3,26	3,30	1,86	1,88	1,89	1,90	1,17	1,15	1,13	1,17
100 km	6,07	6,20	6,29	6,37	3,48	3,50	3,52	3,53	2,40	2,33	2,29	2,26
150 km	8,50	8,46	8,43	8,40	5,37	5,40	5,44	5,47	4,50	4,33	4,23	4,17
200 km	11,62	11,66	11,69	11,71	7,52	7,47	7,43	7,40	15,80	15,56	15,43	15,36
250 km	14,67	14,65	14,64	14,82	11,71	11,52	11,40	11,32	-	-	-	-
300 km	19,67	19,49	19,45	19,42	-	-	-	-	-	-	-	-

Table 4.4: Average power losses in percent of the windfarm's average output power for different windfarm rated power, average wind speed, transmission distances and transmission voltage levels. Part Two

%	1000 MW windfarm											
	132 kV				220 kV				400 kV			
Length	8 m/s	9 m/s	10m/s	11m/s	8 m/s	9 m/s	10m/s	11m/s	8 m/s	9 m/s	10m/s	11m/s
50 km	3,17	3,15	3,14	3,12	1,93	1,96	1,98	2,00	1,17	1,14	1,13	1,12
100 km	5,66	5,70	5,89	5,89	3,63	3,67	3,71	3,74	2,37	2,32	2,36	2,33
150 km	8,65	8,75	8,82	8,87	5,79	5,85	5,89	5,93	4,44	4,30	4,21	4,16
200 km	12,18	12,36	12,49	12,59	7,62	7,58	7,57	7,56	15,51	15,14	14,89	14,72
250 km	15,36	15,38	15,41	15,44	11,62	11,48	11,39	11,30	-	-	-	-
300 km	19,54	19,53	19,47	19,43	-	-	-	-	-	-	-	-

Table 4.5: Average power losses in percent of the windfarm's average output power for different windfarm rated power, average wind speed, transmission distances and transmission voltage levels. Part Three

4.2.1 Modifications and Special Cases of HVAC Transmission Schemes

In this paragraph all the modifications that where made on the layouts of Table 4.1 plus the cases in which the rated power of the windfarm was reduced, are presented. The number and the rated power of the transformers, that from now on will be assumed to be installed in each transmission scheme, are listed in Table 4.6. These configurations will be used for the evaluation of the energy availability and the investment cost. The inputs in the "onshore transformers" category refer only to 132 kV and 220 kV solutions. The losses of each configuration are assumed not change and they are the ones presented in Tables 4.3, 4.4 and 4.5.

Windfarm rated power (MW)	Offshore Transformers	Onshore Transformers
400	400 MVA	**400 MVA**
500	500 MVA	500 MVA
600	2x300 MVA	**600 MVA**
700	300+400 MVA	**300+400 MVA**
800	2x400 MVA	**2x400 MVA**
900	400+500 MVA	**400+500 MVA**
1000	2x300+400 MVA	2x500 MVA

Table 4.6: The offshore and onshore transformers configurations. Grey squares contain the modifications from the original models used in [4.1].

As it was mentioned before a number of cases that are included in Table 4.1 require the use of more cables only to transmit a small amount power from the windfarm. These cases are presented here along with the suggestions for their modifications. It should be noted that in these special cases only the output from the windfarm is modified (and thus the number of cables) and not the number of the transformer units or their rated power. The transformer's modifications are the ones suggested in Table 4.6. The losses for these systems are summarized in Tables 4.7.

- Windfarm rated at 400MW, transmission voltage of 220 kV, transmission distance of 50 km with two installed cables. If instead, the windfarm is rated at 395 MW there is need only for one 220 kV cable. (Modified system A)
- Windfarm rated at 500 MW, transmission voltage of 132 kV, transmission distance of 50 km with three installed cables. If instead, the windfarm is rated at 475 MW there is a need only for two 132 kV cables. (Modified system B)
- Windfarm rated at 700 MW, transmission voltage of 220 kV, transmission distance of 150 km with three installed cables. If instead, the windfarm is rated at 680 MW there is a need only for two 220 kV cables. (Modified system C)
- Windfarm rated at 800 MW, transmission voltage of 220 kV, transmission distance of 50 km with three installed cables. If instead, the windfarm is rated at 790 MW there is a need only for two 220 kV cables. (Modified system D)
- Windfarm rated at 800 MW, transmission voltage of 400 kV, transmission distance of 100 km with two installed cables. If instead, the windfarm is rated at 795 MW there is a need only for one 400 kV cable. (Modified system E)
- Windfarm rated at 900 MW, transmission voltage of 400 kV, transmission distance of 50 km with two installed cables. If instead, the windfarm is rated at 885 MW there is a need only for one 400 kV cable. (Modified system F)

A) 395 MW windfarm, 220 kV transmission voltage, 50 km distance, 1x 220 kV cable				
Average wind speed (m/s)	8	9	10	11
Average power losses (%)	2.0549	2.1287	2.1867	2.2318
B) 475 MW windfarm, 132 kV transmission voltage, 50 km distance, 2x 132 kV cables				
Average wind speed (m/s)	8	9	10	11
Average power losses (%)	3.2263	3.3258	3.4019	3.46

Table 4.7: Losses of modified HVAC systems Part One

C) 680 MW windfarm, 220 kV transmission voltage, 150 km distance, 2x 220 kV cables				
Average wind speed (m/s)	8	9	10	11
Average power losses (%)	5.7737	5.8431	5.9043	5.9547
D) 790 MW windfarm, 220 kV transmission voltage, 50 km distance, 2x 220 kV cables				
Average wind speed (m/s)	8	9	10	11
Average power losses (%)	2.1561	2.2175	2.2652	2.3016
E) 795 MW windfarm, 400 kV transmission voltage, 100 km distance, 1x 400 kV cable				
Average wind speed (m/s)	8	9	10	11
Average power losses (%)	2.7997	2.7866	2.7880	2.7945
F) 885 MW windfarm, 400 kV transmission voltage, 50 km distance, 1x 400 kV cables				
Average wind speed (m/s)	8	9	10	11
Average power losses (%)	1.4093	1.4392	1.4648	1.4855

Table 4.7: Losses of modified HVAC systems Part Two

If the losses of the original and the modified systems are compared one can see that the modified systems appear to have larger losses. It will be obvious though later that the investment cost for the modified systems is significantly less, resulting in a reduction of the transmission cost for the modified systems.

4.3 HVDC LCC Transmission Schemes

Barberis [4.2] based his choices for the HVDC LCC transmission systems on existing projects. These existing projects are the following:

- 600 MW converter station (CS), based on Baltic Cable Project
- 500 MW CS, based on Fennoskan Project
- 440 MW CS, based on Skagerrak pole 3 Project
- 300 MW CS, based on Konti-Skan pole 2 Project
- 250 MW CS, based on Moyle Interconnector Project
- 130 MW CS, based on Gotland poles 2+3 Project

For more information about the characteristics of the project see [4.2]. All the converter stations are in single pole configuration, but if two converter stations are installed for the transmission from the same wind farm, then only one AC filter for each pair of converters (offshore and onshore) is considered both for the losses evaluation ([4.2]) and also for the energy availability calculations. Unlike HVAC systems, in HVDC LCC the number of cables used does not depend on the transmission distance, since no problems with reactive power production along the cable can occur. Each pole uses a single cable for the transmission and in a case of bipole systems the two converter stations are assumed to have the same return path for the current. So, the layout of each pole in general is two converter stations (onshore and offshore) and the cable that interconnects them.

The types of cables used for these transmission systems are Mass Impregnated (MI) cables. The data for these cables are presented in Table 4.8. The converter station, with which each cable is used, is the one with the corresponding rated power.

Rated power [MW]	130	250	300	440	500	600
Voltage level [kV]	150	250	285	350	400	450
Nominal current [kA]	0,867	1	1,053	1,257	1,25	1,333
Material	Copper	Copper	Copper	Copper	Copper	Copper
Cable section [mm^2]	800	1000	1200	1400	1200	1600
Resistance [Ω/km] @ 20 °C	0,0224	0,0177	0,0151	0,0129	0,0151	0,0113
Kind of insulator	MI	MI	MI	Mi	Mi	Mi
Max operating temperature [°C]	55	55	55	55	55	55
Temperature of the ambient [°C]	15					

Table 4.8: Cables data for the HVDC LCC model [4.2]

The several combinations of converter stations that were used for the calculation of the losses in [4.2] are presented in Tables 4.9 and 4.10. The average power losses of each configuration, as a percentage of the windfarm's average output power (Table 3.1), are also given according to the transmission distance and the average wind speed. Exactly the same configurations will be used for the calculation of the energy availability and the evaluation of the investment cost.

%	400 MW windfarm											
	440 CS				500 CS				2x250 CS			
Length	8 m/s	9 m/s	10m/s	11m/s	8 m/s	9 m/s	10m/s	11m/s	8 m/s	9 m/s	10m/s	11m/s
50 km	1,8499	1,795	1,7602	1,7375	1,8971	1,8316	1,7898	1,7623	1,8477	1,8189	1,8014	1,7906
100 km	2,0215	1,9777	1,9511	1,9344	2,0473	1,9914	1,9566	1,9343	2,0958	2,0766	2,0662	2,0606
150 km	2,193	2,1604	2,1419	2,1313	2,1975	2,1512	2,1234	2,1063	2,3439	2,3343	2,331	2,3307
200 km	2,3646	2,3431	2,3328	2,3282	2,3478	2,311	2,2902	2,2782	2,592	2,592	2,5958	2,6007
250 km	2,5362	2,5258	2,5237	2,525	2,498	2,4708	2,457	2,4502	2,8401	2,8498	2,8606	2,8708
300 km	2,7077	2,7086	2,7145	2,7219	2,6482	2,6306	2,6238	2,6222	3,0882	3,1075	3,1254	3,1408

%	500 MW windfarm											
	500 CS				2 x 250 CS				600 CS			
Length	8 m/s	9 m/s	10m/s	11m/s	8 m/s	9 m/s	10m/s	11m/s	8 m/s	9 m/s	10m/s	11m/s
50 km	1,8291	1,7819	1,7523	1,7332	1,8396	1,822	1,812	1,8063	1,8357	1,7708	1,7292	1,7017
100 km	2,0254	1,9912	1,971	1,9587	2,1644	2,1598	2,1594	2,1608	1,9475	1,8896	1,8532	1,8295
150 km	2,2218	2,2004	2,1896	2,1843	2,4891	2,4977	2,5069	2,5153	2,0592	2,0085	1,9772	1,9573
200 km	2,4182	2,4097	2,4083	2,4098	2,8139	2,8356	2,8543	2,8699	2,1709	2,1273	2,1012	2,0851
250 km	2,6146	2,619	2,6269	2,6354	3,1386	3,1734	3,2018	3,2244	2,2826	2,2461	2,2252	2,2129
300 km	2,811	2,8283	2,8456	2,8609	3,4633	3,5113	3,5492	3,5789	2,3944	2,365	2,3492	2,3407

%	600 MW windfarm											
	600 CS				440 CS + 250 CS				2 x 300 CS			
Length	8 m/s	9 m/s	10m/s	11m/s	8 m/s	9 m/s	10m/s	11m/s	8 m/s	9 m/s	10m/s	11m/s
50 km	1,7718	1,7208	1,6885	1,6674	1,6081	1,612	1,6193	1,627	1,7704	1,75	1,7379	1,7307
100 km	1,9109	1,869	1,8433	1,8271	1,8343	1,8438	1,8551	1,8658	2,026	2,0158	2,0112	2,0095
150 km	2,05	2,0172	1,9982	1,9867	2,0606	2,0755	2,0909	2,1046	2,2816	2,2816	2,2845	2,2883
200 km	2,1892	2,1654	2,153	2,1464	2,2868	2,3072	2,3267	2,3434	2,5372	2,5474	2,5578	2,5671
250 km	2,3283	2,3136	2,3078	2,3061	2,5131	2,5389	2,5624	2,5822	2,7928	2,8132	2,8311	2,8459
300 km	2,4674	2,4618	2,4626	2,4658	2,7393	2,7706	2,7982	2,821	3,0484	3,079	3,1044	3,1248

%	700 MW windfarm											
	500 CS + 250 CS				440 CS + 300 CS				3 x 250 CS			
Length	8 m/s	9 m/s	10m/s	11m/s	8 m/s	9 m/s	10m/s	11m/s	8 m/s	9 m/s	10m/s	11m/s
50 km	1,603	1,6097	1,6187	1,6276	1,6701	1,662	1,6591	1,6586	1,8146	1,7995	1,7909	1,7859
100 km	1,851	1,8632	1,8763	1,8883	1,8858	1,8857	1,8886	1,8925	2,131	2,1239	2,1211	2,1204
150 km	2,099	2,1166	2,1338	2,1489	2,1016	2,1093	2,1181	2,1263	2,4474	2,4484	2,4514	2,455
200 km	2,3471	2,3701	2,3914	2,4096	2,3174	2,3329	2,3476	2,3602	2,7637	2,7728	2,7817	2,7896
250 km	2,5951	2,6235	2,6489	2,6702	2,5331	2,5566	2,5771	2,594	3,0801	3,0972	3,112	3,1241
300 km	2,8431	2,877	2,9065	2,9308	2,7489	2,7802	2,8066	2,8279	3,3965	3,4216	3,4423	3,4587

%	700 MW windfarm											
	600 CS + 130 CS											
Length	8 m/s	9 m/s	10m/s	11m/s	8 m/s	9 m/s	10m/s	11m/s	8 m/s	9 m/s	10m/s	11m/s
50 km	1,3918	1,4313	1,4648	1,492								
100 km	1,5953	1,6455	1,6873	1,7207								
150 km	1,7988	1,8597	1,9098	1,9493								
200 km	2,0022	2,0739	2,1323	2,178								
250 km	2,2057	2,288	2,3548	2,4066								
300 km	2,4092	2,5022	2,5773	2,6353								

Table 4.9: Average power losses (in percent of average input power) of several HVDC LCC transmission systems [4.2]. Part One. CS: Converter Station

%	800 MW windfarm											
	500 CS + 300 CS				2 x 440 CS				600 CS + 250 CS			
Length	8 m/s	9 m/s	10m/s	11m/s	8 m/s	9 m/s	10m/s	11m/s	8 m/s	9 m/s	10m/s	11m/s
50 km	1,6647	1,6599	1,6591	1,6601	1,737	1,7107	1,6945	1,6844	1,4975	1,5158	1,533	1,5478
100 km	1,8984	1,9018	1,9072	1,9127	1,9254	1,9064	1,8956	1,8894	1,6846	1,7102	1,7329	1,7518
150 km	2,1321	2,1437	2,1553	2,1654	2,1138	2,1021	2,0967	2,0945	1,8718	1,9046	1,9328	1,9559
200 km	2,3658	2,3857	2,4034	2,4181	2,3022	2,2979	2,2979	2,2995	2,0589	2,099	2,1327	2,16
250 km	2,5995	2,6276	2,6515	2,6708	2,4906	2,4936	2,499	2,5046	2,246	2,2934	2,3326	2,364
300 km	2,8332	2,8695	2,8996	2,9235	2,679	2,6893	2,7001	2,7096	2,4332	2,4878	2,5325	2,5681
%	900 MW windfarm											
	3 x 300 CS				600 CS + 300 CS				500 CS + 440 CS			
Length	8 m/s	9 m/s	10m/s	11m/s	8 m/s	9 m/s	10m/s	11m/s	8 m/s	9 m/s	10m/s	11m/s
50 km	1,7482	1,7337	1,7272	1,7219	1,5364	1,5432	1,5188	1,5335	1,727	1,7045	1,6909	1,6824
100 km	2,0197	2,0122	2,0038	2,0034	1,7376	1,7488	1,7184	1,7371	1,9322	1,9172	1,909	1,9045
150 km	2,2912	2,2907	2,2803	2,2849	1,9388	1,9543	1,9179	1,9407	2,1373	2,1298	2,1271	2,1266
200 km	2,5627	2,5693	2,5569	2,5664	2,1401	2,1598	2,1174	2,1443	2,3425	2,3424	2,3452	2,3487
250 km	2,8343	2,8478	2,8335	2,848	2,3413	2,3654	2,3169	2,3479	2,5477	2,555	2,5633	2,5708
300 km	3,1058	3,1263	3,1101	3,1295	2,5426	2,5709	2,5164	2,5515	2,7528	2,7676	2,7814	2,7929
%	1000 MW windfarm											
	2 x 500 CS				600 CS + 440 CS				500 CS + 600 CS			
Length	8 m/s	9 m/s	10m/s	11m/s	8 m/s	9 m/s	10m/s	11m/s	8 m/s	9 m/s	10m/s	11m/s
50 km	1,7301	1,7081	1,6949	1,6868	1,6221	1,6122	1,6078	1,6063	1,7074	1,6811	1,6648	1,6544
100 km	1,9455	1,9322	1,9252	1,9216	1,7925	1,7888	1,7891	1,791	1,8782	1,8562	1,8431	1,835
150 km	2,161	2,1562	2,1555	2,1565	1,9629	1,9654	1,9703	1,9756	2,0489	2,0313	2,0214	2,0156
200 km	2,3764	2,3802	2,3858	2,3914	2,1333	2,142	2,1516	2,1603	2,2196	2,2064	2,1996	2,1962
250 km	2,5919	2,6042	2,6161	2,6262	2,3037	2,3186	2,3328	2,345	2,3904	2,3815	2,3779	2,3767
300 km	2,8073	2,8283	2,8464	2,8611	2,4741	2,4952	2,5141	2,5296	2,5611	2,5565	2,5561	2,5573
%	1000 MW windfarm											
	2 x 600 CS											
Length	8 m/s	9 m/s	10m/s	11m/s	8 m/s	9 m/s	10m/s	11m/s	8 m/s	9 m/s	10m/s	11m/s
50 km	1,7048	1,6729	1,653	1,6401								
100 km	1,8273	1,8001	1,7836	1,7732								
150 km	1,9498	1,9273	1,9142	1,9063								
200 km	2,0723	2,0545	2,0448	2,0394								
250 km	2,1948	2,1817	2,1754	2,1725								
300 km	2,3173	2,3088	2,306	2,3056								

Table 4.10: Average power losses (in percent of average input power) of several HVDC LCC transmission systems [4.2]. Part Two. CS: Converter Station

4.4 HVDC VSC Transmission Schemes

As in LCC systems, the choice of the configurations for HVDC VSC transmission systems was based on real projects. These projects are:

- The 330 MW HVDC VSC link named as Cross-Sound cable link

- The 220 MW HVDC VSC link named as Murray link

More information about the specific links are given in Table 2.1. Barberis [4.2] also evaluated the losses of a 500 MW transmission system based on data from the two aforementioned projects. The general layout of each VSC transmission system is shown in Figure 4.2, where the two blocks labeled as "Station 1 and 2" represent the offshore and onshore converters respectively, and the cable pair that interconnects them is represented by the block labeled as "Cable".

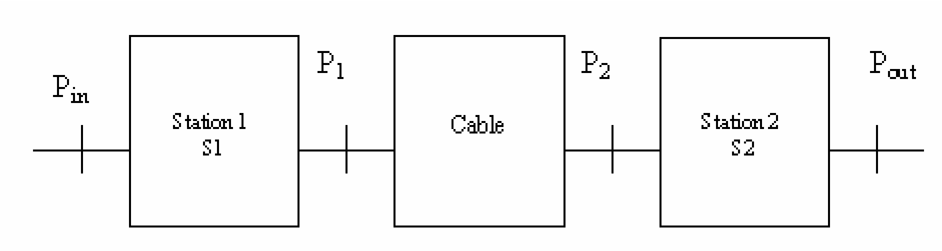

Figure 4.2: HVDC VSC Transmission System block diagram

The technical characteristics of the cables that were used in each transmission system are given in Table 4.11.

Rated power [MW]	220	350	500
Nominal current [kA]	0,793	1,2	1,677
Material	Copper	Copper	Copper
Cable section [mm^2]	1300	1300	2000
Resistance [Ω/km] @ 20 °C	0.0138	0.0138	0.009
Kind of insulator	Polymeric	Polymeric	Polymeric
Max operating temperature [°C]	70	70	70
Temperature of the ambient [°C]	15		

Table 4.11: Cables data for the model for the chosen HVDC VSC transmission systems [4.2]

The several combinations of converter stations that were used for the calculation of the losses in [4.2] are presented in Tables 4.12 and 4.13. The average power losses of each configuration, as a percentage of the windfarm's average output power (Table 3.1), are also given according to the transmission distance and the average wind speed. Exactly the same configurations will be used for the calculation of the energy availability and the evaluation of the investment cost for VSC systems.

%	400 MW windfarm											
	2x220 MW CS, 2x220 MW CP				500 MW CS, 1x500 MW CP				2x220 MW CS, 1x500 MW CP			
Length	8 m/s	9 m/s	10m/s	11m/s	8 m/s	9 m/s	10m/s	11m/s	8 m/s	9 m/s	10m/s	11m/s
50 km	4,56	4,40	4,29	4,22	4,67	4,44	4,29	4,19	4,80	4,61	4,48	4,40
100 km	4,84	4,68	4,59	4,52	4,99	4,78	4,64	4,56	5,12	4,94	4,83	4,76
150 km	5,11	4,97	4,88	4,82	5,30	5,11	4,99	4,92	5,43	5,28	5,18	5,12
200 km	5,39	5,26	5,18	5,12	5,62	5,45	5,35	5,28	5,75	5,61	5,53	5,48
250 km	5,66	5,54	5,47	5,42	5,94	5,79	5,70	5,64	6,06	5,95	5,88	5,85
300 km	5,94	5,83	5,76	5,73	6,25	6,12	6,05	6,01	6,38	6,29	6,23	6,21
%	500 MW windfarm											
	350+220 MW CS, 350+220 MW CP				2x350 MW CS, 2x350 MW CP				1x500 MW CS,1x500 MW CP			
Length	8 m/s	9 m/s	10m/s	11m/s	8 m/s	9 m/s	10m/s	11m/s	8 m/s	9 m/s	10m/s	11m/s
50 km	4,15	4,05	3,98	3,93	4,34	4,21	4,13	4,07	4,57	4,43	4,34	4,29
100 km	4,53	4,43	4,37	4,33	4,70	4,58	4,50	4,45	4,98	4,87	4,80	4,76
150 km	4,90	4,82	4,76	4,73	5,06	4,94	4,87	4,82	5,39	5,31	5,26	5,23
200 km	5,28	5,20	5,16	5,12	5,41	5,30	5,24	5,19	5,80	5,75	5,72	5,71
250 km	5,66	5,59	5,55	5,52	5,77	5,67	5,61	5,56	6,22	6,19	6,19	6,19
300 km	6,03	5,98	5,94	5,92	6,13	6,03	5,97	5,94	6,63	6,63	6,65	6,67
%	500 MW windfarm											
	350+220 MW CS, 1x500 MW CP				2x350 MW CS, 1x500 MW CP							
Length	8 m/s	9 m/s	10m/s	11m/s	8 m/s	9 m/s	10m/s	11m/s	8 m/s	9 m/s	10m/s	11m/s
50 km	4,19	4,10	4,05	4,02	4,36	4,24	4,17	4,12				
100 km	4,61	4,55	4,52	4,50	4,78	4,69	4,64	4,60				
150 km	5,03	5,00	4,99	4,98	5,19	5,13	5,10	5,09				
200 km	5,45	5,45	5,46	5,47	5,61	5,58	5,57	5,57				
250 km	5,87	5,90	5,93	5,95	6,03	6,03	6,04	6,05				
300 km	6,29	6,34	6,39	6,44	6,45	6,48	6,51	6,54				
%	600 MW windfarm											
	2x350 MW CS, 2x350 MW CP				500+220 MW CS, 500+220 MW CP							
Length	8 m/s	9 m/s	10m/s	11m/s	8 m/s	9 m/s	10m/s	11m/s	8 m/s	9 m/s	10m/s	11m/s
50 km	4,19	4,10	4,04	4,00	4,05	3,97	3,92	3,89				
100 km	4,60	4,52	4,47	4,44	4,42	4,35	4,30	4,27				
150 km	5,00	4,94	4,90	4,88	4,80	4,73	4,68	4,65				
200 km	5,40	5,36	5,33	5,32	5,17	5,11	5,07	5,04				
250 km	5,80	5,77	5,76	5,76	5,54	5,48	5,45	5,42				
300 km	6,21	6,19	6,19	6,20	5,91	5,86	5,83	5,80				

Table 4.12: Average power losses (in percent of average input power) of several HVDC VSC transmission systems [4.2]. CS: converter Station, CP: cable pairs

Part One.

%	700 MW windfarm											
	2x350 MW CS, 2x350 MW CP				500+220 MW CS, 500+220 MW CP							
Length	8 m/s	9 m/s	10m/s	11m/s	8 m/s	9 m/s	10m/s	11m/s	8 m/s	9 m/s	10m/s	11m/s
50 km	4,22	4,18	4,16	4,15	4,07	4,01	3,98	3,96				
100 km	4,70	4,68	4,67	4,67	4,47	4,43	4,41	4,40				
150 km	5,19	5,18	5,19	5,20	4,88	4,85	4,84	4,84				
200 km	5,67	5,69	5,71	5,73	5,28	5,27	5,27	5,27				
250 km	6,16	6,20	6,23	6,26	5,69	5,69	5,70	5,71				
300 km	6,65	6,70	6,75	6,79	6,10	6,11	6,13	6,15				
%	800 MW windfarm											
	2x350+220 MW CS,2x 350+220 MW CP				3x350 MW CS, 3x350 MW CP				500+350 MW CS, 500+350 MW CP			
Length	8 m/s	9 m/s	10m/s	11m/s	8 m/s	9 m/s	10m/s	11m/s	8 m/s	9 m/s	10m/s	11m/s
50 km	3,99	3,95	3,92	3,91	4,16	4,08	4,02	3,99	4,08	4,05	4,03	4,02
100 km	4,40	4,36	4,34	4,33	4,59	4,51	4,45	4,42	4,52	4,50	4,49	4,49
150 km	4,81	4,78	4,76	4,75	5,02	4,94	4,88	4,85	4,96	4,96	4,96	4,97
200 km	5,22	5,19	5,18	5,17	5,45	5,37	5,31	5,28	5,39	5,41	5,43	5,45
250 km	5,62	5,61	5,59	5,59	5,88	5,80	5,75	5,71	5,83	5,87	5,90	5,92
300 km	6,03	6,02	6,01	6,01	6,31	6,23	6,18	6,14	6,27	6,32	6,37	6,40
%	900 MW windfarm											
	3x350 MW CS, 3x350 MW CP				2x500 MW CS, 2x500 MW CP				2x350+220 MW CS,2x 350+220 MW CP			
Length	8 m/s	9 m/s	10m/s	11m/s	8 m/s	9 m/s	10m/s	11m/s	8 m/s	9 m/s	10m/s	11m/s
50 km	4,07	4,02	3,99	3,96	4,05	4,00	3,97	3,95	4,02	4,00	4,00	4,00
100 km	4,52	4,47	4,45	4,43	4,45	4,42	4,40	4,39	4,46	4,46	4,46	4,47
150 km	4,97	4,93	4,90	4,89	4,85	4,83	4,83	4,82	4,91	4,92	4,93	4,94
200 km	5,41	5,38	5,36	5,35	5,25	5,25	5,25	5,26	5,35	5,37	5,39	5,41
250 km	5,86	5,84	5,82	5,82	5,65	5,66	5,68	5,70	5,80	5,83	5,86	5,89
300 km	6,31	6,29	6,28	6,28	6,05	6,08	6,11	6,13	6,24	6,29	6,33	6,36
%	1000 MW windfarm											
	3x350 MW CS, 3x350 MW CP				2x500 MW CS, 2x500 MW CP							
Length	8 m/s	9 m/s	10m/s	11m/s	8 m/s	9 m/s	10m/s	11m/s	8 m/s	9 m/s	10m/s	11m/s
50 km	4,09	4,06	4,05	4,03	4,11	4,09	4,08	4,08				
100 km	4,59	4,57	4,56	4,56	4,56	4,56	4,57	4,57				
150 km	5,09	5,08	5,08	5,08	5,01	5,03	5,05	5,07				
200 km	5,59	5,59	5,59	5,60	5,47	5,51	5,54	5,56				
250 km	6,08	6,10	6,11	6,12	5,92	5,98	6,03	6,06				
300 km	6,58	6,61	6,63	6,64	6,38	6,45	6,51	6,56				

Table 4.13: Average power losses (in percent of average input power) of several HVDC VSC transmission systems [4.2]. CS: converter Station, CP: cable pairs

Part Two.

4.5 Summary

In order to be able to evaluate the availability and investment cost of a transmission system, the specific layout configuration has to be known. In this chapter the configurations for all three transmission technologies (HVAC, HVDC VSC and HVDC LCC) are described in detail. The specific layouts were choices of Todorovic [4.1] and Barberis [4.2] that also provided the average losses estimations. The losses constitute one of the major inputs to the energy transmission cost model that will be presented later in this study. Wherever possible, assumptions and modifications were made upon the originally selected transmission layouts, in order to improve their rated power capacity according to the requirements of the windfarm size.

4.6 References

[4.1] Todorovic J., "Losses Evaluation of HVAC Connection for Large Offshore Wind Farms", Masters Thesis, Department of Electrical Engineering, Royal Institute of Technology, Stockholm, Sweden, 2004

[4.2] Barberis N., "Evaluation of Losses of HVDC Solutions for Large Offshore Wind Farms", Masters Thesis, Department of Electrical Engineering, KTH, Stockholm, Sweden, 2005

5

Energy Availability of Transmission Systems

5.1 Introduction

The role of a transmission system is to act in between production and consumption of electrical energy. In the cases studied here, it is assumed that the consumer is located at the end of the transmission line and all the energy delivered at that point will be sold. The task is to determine the system that will transmit energy with the lowest cost. Three are the major categories that contribute to the energy transmission cost:

- The initial investment cost,
- The losses in the transmission line
- The energy unavailability of the transmission system.

This section focuses on the investigation of the energy unavailability of the transmission systems that were presented in the previous chapter. The energy unavailability is defined as the percentage of the energy produced by the windfarm that could not be transmitted as a result of failures in the transmission system (forced outages). Maintenance (scheduled outages) is another factor that contributes to the energy availability of a transmission system. In this study though, it is assumed that maintenance takes place during periods with low wind speeds and thus its contribution to the availability of the system is minimal.

For the calculation of the energy unavailability an algorithm has been developed with respect to the special characteristics that a transmission system connected to a windfarm presents. Namely, the production in a wind power plant does not follow the demand for electrical energy but the speed of the wind. For this reason the Rayleigh distribution assumed for the wind speed and the aggregated model for the windfarm, presented in Chapter 3, will be used to define the input to the transmission systems. The analysis will be based on statistical data of the reliability for the different components of each transmission technology (HVAC, HVDC LCC, and HVDC VSC).

5.2 HVDC LCC

An HVDC LCC transmission system connected to a windfarm has the basic configuration that is presented in Figure 5.1. There is one offshore converter station connected to the windfarm, one onshore converter station connected to the main grid and the DC cable that interconnects the two converter stations.

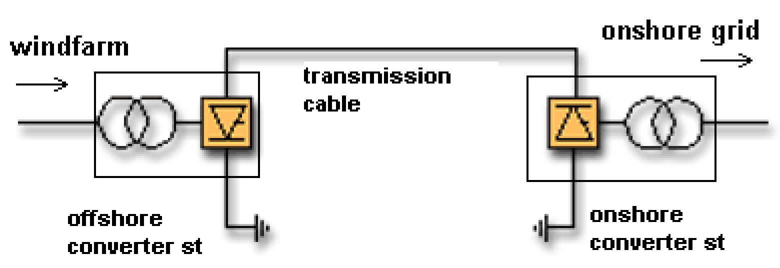

Figure 5.1: Basic configuration of a HVDC LCC transmission line from an offshore windfarm.

In Paragraph 2.2, a detailed analysis of the several components that a converter station includes (such as the converter transformer, the thyristor valves, AC and DC filters etc) was given. Failures occur to all of these components and all of them contribute to the unavailability of the system. Thus, it is very important to know the failure rate of each component that is included. For this reason, statistical data of HVDC LCC systems availability were collected and analyzed. The major source for statistical data was the CIGRE reliability reports [5.1], [5.2], [5.3], [5.4]. In these reports, the reliability of several HVDC LCC transmission systems throughout the world is being presented annually. Reports with data from 1993 to 2002 were analyzed. The number of forced outages and the equivalent outage hours for all the components of a transmission system, for the specific year, are summarized. The equivalent outage hours represent the hours that the transmission system was not operating due to a fault in a specific component. In these reports the data on forced outages are classified into six categories as follows:

- AC and auxiliary equipment (AC-E)
- Valves (V)
- Control and Protection (C&P)
- DC equipment (DC-E)
- Other (O)
- Transmission line or Cable (TLC)

Only data from systems that had technological similarities to the ones used in this study were included in the analysis. For example, statistics from projects involving

Back-to-Back converter technology were not included. Data for overhead lines and buried cables were ignored, and only cases with submarine, mass impregnated insulation cables were analyzed. The information concerning the type of the cable used and its total length were provided by several sources [5.5], [5.6] [5.7], [5.8], [5.9]. The type of the converter station was noted within the CIGRE reports. It has to be noticed that none of the HVDC converters of the reports mentioned above are situated offshore. It will be assumed though that the several components will present the same availability in the highly corrosive offshore environment. The same assumption applies for the cases of HVAC and HVDC VSC.

5.2.1 Calculation of the Unavailability of Each Component

For the calculation of the unavailability of each component within the converter station a simple formula was used:

$$C_i = \frac{\sum h_i}{(pole \cdot years) \cdot 365 \cdot 24} \cdot 100\% \qquad \text{(Eq: 5.1)}$$

Where:

C_i = the unavailability of component i in percent,

$pole \cdot years$ = the number of poles studied multiplied to the corresponding number of years, for which data existed,

$\sum h_i$ = the total outage hours of component i for all poles and all years for which data existed.

The unavailability of the cables was made using the following formula:

$$C_{cable} = \frac{\sum h_{cable}}{(km \cdot years) \cdot 365 \cdot 24} \cdot 100\% \qquad \text{(Eq: 5.2)}$$

Where:

C_{cable} = the percent unavailability of the cable per km,

$km \cdot years$ = the total km of the cables multiplied to the number of years for which data existed,

$\sum h_{cable}$ = the total outage hours of the cables for the years for which data existed.

Totally data for 222 $pole \cdot years$ and 13301 $km \cdot years$ of cables were included. The calculated average unavailability of each component is summarized in Table 5.1. The data refer to both the transmitting and receiving station.

	Converter Transformers	AC auxiliary equipment	Thyristor Valves	DC equipment	Protection and control	Other	Submarine cable
Unavailability (%)	0.9251	0.1397	0.1175	0.0647	0.0545	0.0124	0.4462$^{(1)}$

(1) Per 100km

Table 5.1: Average time unavailability for each component of a HVDC LCC transmission system

There are some details concerning the calculation of the average unavailability that should be noted. In the CIGRE reports the converter transformers were not classified in a separate category but only as a part of "AC and Auxiliary equipment ". Nevertheless, every time a fault occurred in the converter transformer this was noted and thus it was possible to calculate the unavailability only for the transformers. The same applies for the submarine cables. In the CIGRE reports the submarine cables were included "Transmission Line or Cable" category but faults in the cables were always noted.

5.2.2 Facts Concerning Cables Reliability

As it was mentioned before, data from 13301 $km \cdot years$ of cables were used. These data refer to 11 existing HVDC LCC links with submarine cables. For some reason, (bad design or areas with heavy sea traffic) faults occurred only in three of theses links. These cases are presented in Table 5.2. If statistics for more years (especially from links that seem to operate without cable faults) were available, it would be possible to have rather different cable unavailability.

	Number of failures (in brackets) and total outage hours									
	1991	1993	1994	1997	1998	1999	2000	2001	2002	2003
Skagerrak 1&2	-	0	0	0	0	0	0	0	(1) 908,1	-
Fennoskan	(1) 1121	0	0	0	0	0	0	0	0	(1) 1690
SwePol	-	-	-	-	-	-	-	0	(6) 1480	-

Table 5.2: Number of failures and total outage hours for submarine cables in the three cases of study in which failures appear.

There are several reasons for which failures in a submarine cable can occur such as faults in the insulation, faults caused by bad design or installation or even faults caused by the effect of the environment (armour corrosion, sheath failure). While the faults mentioned above have to do generally with the design and technology used for the manufacture of the cable, some fault are caused by third party factors. There are numerous cases of failures in submarine cables caused by fishing nets, anchors or ship contact. The failures caused by the latter factors depend greatly on the geography of the area and the condition of the seabed. There is a much larger danger of cable failure in areas with heavy naval traffic and shallow waters, while cable suspension over rocky areas was a frequent cause of failures in early submarine schemes which did not use extensive seabed surveys.

According to data provided by the "Scottish and Southern Energy" [5.14] concerning their submarine cables statistics up to the year 2001, 30.3% of the cable failures are caused by fishing nets or contact with anchors and ships. This number refers to cables directly laid on the sea bed and reflects the need for cable burial to decrease the probability of a fault. Even though the above mentioned data refer to AC cables with a voltage rating of 11 and 33 kV, it provides good information concerning the "external" factors that contribute to the cable's unavailability.

It is also very important to investigate the period of time that is required for a submarine cable to be repaired. According to [5.14] the time to repair a fault can vary a great deal. The problems of locating and pinpointing the fault are difficult on solid cables as the prevailing sea and weather conditions limit the working time. Undersea cables will need to be inspected by divers or submersible cameras to pinpoint the fault and the extend of the damage. A lot of time is taken in mobilizing the right ship or barge, equipping it with the cable handling plant, replacement cable and taking it to the site in order to replace the cable. The actual jointing for solid cables can take up a couple of days for each joint. Faults on solid insulation cables can take up to 3 months to be repaired, also depending on the time that takes for the cable manufacturer to provide the replacement if there is no emergency stock held.

5.2.3 Method for Calculating Energy Unavailability of HVDC LCC Transmission Systems.

<u>First Case: Single Pole Transmission System-Continuously Producing Power Plant</u>

First it will be assumed to have a single pole HVDC LCC transmission system. For the unavailability study the system can represented schematically as in Figure 5.2. The different components that contribute to the total system's unavailability are represented as blocks. The unavailability of each component is the one given in Table 5.1.

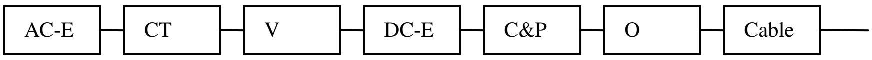

Figure 5.2: Schematic representation of a monopole HVDC LCC system for availability study. (AC-E: AC auxiliary equipment, CT: Converter transformer, V: Valves, DC-E: DC equipment, C&P: Control and Protection, O: Other, Cable: Submarine cable)

As defined before, energy unavailability is the percentage of the energy produced by the windfarm that could not be transmitted as a result of failures in the transmission system. Based on this, the following formula is introduced representing the ratio of the energy that could not be delivered due to forced outages, over the energy that could have been transmitted if we did not have any forced outages.

$$Un = \frac{Energy \quad not \quad transmitted}{Energy \quad that \quad could \quad have \quad been \quad transmitted} \qquad \text{(Eq: 5.3)}$$

Equation 5.3 describes generally the method used to calculate the energy unavailability of a transmission system.

For every different component of the transmission system, the unavailability can be considered as the probability that the specific component will not be operating due to a fault. If, for example, the state in which AC-E is not operating is named O_{AC-E}, then, according to Table 5.1, the probability (F) of this state will be $F(O_{AC-E}) = 0.001397$. In the same way, states O_{CT}, O_V, O_{DC-E}, $O_{C\&P}$, O_{Cable}, O_O are introduced for the transformers, valves, DC equipment, Control and Protection, Cable and Other respectively. The probability of each state is given in Table 5.1

(in %). Also state O_{Tot} is introduced, during which the total system of Figure 5.2 is not operating. For the transmission line of Figure 5.2 the probability that will not operate due to a fault will be:

$$F(O_{Tot}) = F(O_{AC-E} \cup O_{Trans} \cup O_{Valves} \cup O_{DC-E} \cup O_{C\&P} \cup O_{O} \cup O_{Cable}) \quad \text{(Eq: 5.4)}$$

In a serial system (like the one in Figure 5.2) it is assumed that only faults at one component at a time can occur. If for example a fault occurs in the transformer and the fault is being repaired, the rest of the components are not operating thus no fault can occur to them. In other words states $O_{AC-E}, O_{Trans}, O_{Valves}, O_{DC-E}, O_{C\&P}, O_{Cable}, O_{O}$ are disjoint (see [5.10] for more details). In this case Equation 5.4 can be rewritten as:

$$F(O_{Tot}) = F(O_{AC-E}) + F(O_{Trans}) + F(O_{Valves}) + F(O_{DC-E}) + F(O_{C\&P}) + F(O_{O}) + F(O_{Cable})$$
(Eq: 5.5)

If the cable length is 100 km then $F(O_{Cable}) = 0{,}004462$. For the total system according to Table 5.1 and equation 5.5 it will be $F(O_{Tot}) = 0.017601$. If the period of study is *t* (hours) and the input power to the transmission system is *P* (Watt) then according to Equation 5.3 it will be:

$$Un = \frac{P \cdot t \cdot F(O_{Tot})}{P \cdot t} = F(O_{Tot}) \quad \text{(Eq.: 5.6)}$$

In the next table the total unavailability of the system for different cable lengths is presented:

Transmission Distance (km)	50	100	150	200	250	300
Unavailability (%)	1.5370	1.7601	1.9832	2.2063	2.4294	2.6525

Table 5.2: Energy Unavailability of the system described in Figure 5.2 for different transmission lengths

Second Case: Two Parallel Transmission Systems-Continuously Producing Power Plant

Next a more complex system will be investigated, namely two poles operating in parallel. The two poles have different power transmission capabilities. It is assumed that power has to be transmitted from a plant that produces 700 MW continuously. One pole is rated at 500 MW and the other at 250 MW. The two poles use common AC filters (AC auxiliary equipment). The transmission length is 100 km. The system is schematically represented in Figure 5.3.

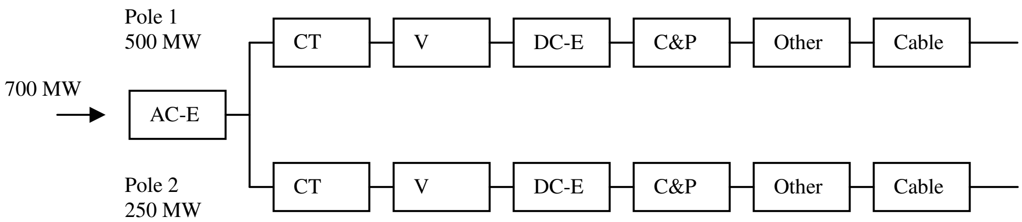

Figure 5.3: Schematic representation of a bipole HVDC LCC system for availability study. (AC-E: AC auxiliary equipment, CT: Converter transformer, V: Valves, DC-E: DC equipment, C&P: Control and Protection, O: Other, Cable: Submarine cable)

First the unavailability of the two parallel systems without the AC auxiliary equipment will be examined.

- For Pole 1:

$$F(O_{Pole1}) = F(O_{CT}) + F(O_V) + F(O_{DC-E}) + F(O_{C\&P}) + F(O_O) + F(O_{Cable}) \quad \text{(Eq:5.7)}$$

$$F(O_{Pole1}) = 0{,}016204$$

- For Pole 2:

$$F(O_{Pole2}) = F(O_{CT}) + F(O_V) + F(O_{DC-E}) + F(O_{C\&P}) + F(O_O) + F(O_{Cable}) \quad \text{(Eq: 5.8)}$$

$$F(O_{Pole2}) = 0{,}016204$$

As it can be observed the two poles have the same probabilities of not operating due to faults in their components. The difference is that four different “modes” exist in which the system can be found operating. Theses different modes are:

- Pole 1 “ON” , Pole 2 “ON”

- Pole 1 “ON” , Pole 2 “OFF”
- Pole 1 “OFF”, Pole 2 “ON”
- Pole 1 “OFF”, Pole 2 “OFF”

Each mode has a different power transmission capability and a different probability to occur. The different modes of operation are summarized in Table 5.3.

MODE 1			MODE 2			MODE 3			MODE 4		
	Transmission Capability (MW)	Probabili-ty		Transmission Capability (MW)	Probabili-ty		Transmission Capability (MW)	Probabili-ty		Transmission Capability (MW)	Probabili-ty
ON	500	0,983796	ON	500	0,983796	OFF	0	0,016204	OFF	0	0,016204
ON	250	0,983796	OFF	0	0,016204	ON	250	0,983796	OFF	0	0,016204
	750	0,96785		500	0,0159		250	0,0159		0	0,000262

Table 5.3: Operation modes and their probabilities of the parallel pole system described in Figure 5.3

In each operation mode, the state of each pole (ON, OFF) is assumed not to depend on the state of the other pole. It is known that $F(A \cap B) = F(A) \cdot F(B)$ when A and B are independent states [5.10]. Thus, the probability of a specific mode occurring is calculated by multiplying the probabilities of each pole being in the specific state (ON or OFF). According to Table 5.3, for a period of time *t*, the above described transmission system will operate:

- for 96.785% of *t* in mode 1
- for 1.59% of *t* in mode 2
- for 1.59% of *t* in mode 3
- for 0.0262% of *t* in mode 4

As it was mentioned, it is assume to have a power plant as an input to the transmission line that continuously produces 700MW. The total energy unavailability of the two parallel poles (AC-E still not included) can be calculated using Equation 5.3:

$$Un_{pole1\&2} = \frac{Energy \quad not \quad transmitted}{Energy \quad that \quad could \quad have \quad been \quad transmitted} \qquad \text{(Eq: 5.9)}$$

- During mode 1 (96.785% of *t*) all the produced power is being transmitted
- During mode 2 (1.59% of *t*) 200 MW are not being transmitted
- During mode 3 (1.59% of *t*) 450 MW are not being transmitted
- During mode 4 (0.0262% of *t*) 700 MW are not being transmitted

The energy that would have been transmitted if there were no force outages is $700 \cdot t$ MWh. So the unavailability of the two parallel poles is:

$$Un_{pole1\&2} = \frac{0.96785 \cdot t \cdot 0 + 0.0159 \cdot t \cdot 200 + 0.0159 \cdot t \cdot 450 + 0.000262 \cdot t \cdot 700}{700 \cdot t} \quad \text{(Eq: 5.10)}$$

$$Un_{pole1\&2} = 0.015$$

Now the simple case of two serial components exists, one for the two parallel lines and one for the common AC-E. Thus for the total system:

$$Un_{Tot} = Un_{pole1\&2} + Un_{AC-E} = 0.015 + 0.001397 = 0.0164 \quad \text{(Eq: 5.11)}$$

Or $Un_{Tot} = 1.64\%$

In the next table the total unavailability of the system for different cable lengths is presented:

Transmission Distance (km)	50	100	150	200	250	300
Unavailability (%)	1.44	1.64	1.85	2.06	2.27	2.48

Table 5.4: Energy Unavailability of the system described in figure 5.3 for different transmission lengths. Continuous production of 700 MW.

Third Case: Two Parallel Transmission Systems-Windfarm as an Input to the Transmission System

In the previous case a power plant that continuously produced 700 MW was examined. Now the case of having a wind farm rated at 700 MW as an input to the transmission line is considered. The characteristics of the wind farm (win turbines, wind farm size etc) are the ones described in Paragraph 3.2.2. The transmission line is the same as the one described previously. It is also assumed that in the area of the windfarm the average wind speed is 8m/sec. As it was explained in Chapter 4 the aggregated power curve for a 700 MW wind farm will have the following form:

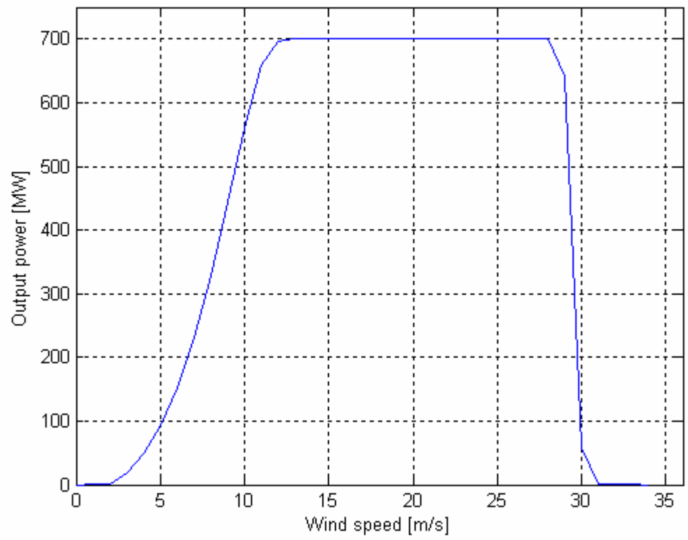

Figure 5.4: Aggregated power curve of a 700 MW wind farm for 8m/sec average wind speed

Also the assumption that the wind speed follows the Rayleigh distribution was made. The Rayleigh distribution of the wind speed for an average speed of 8 m/sec is shown in the next figure:

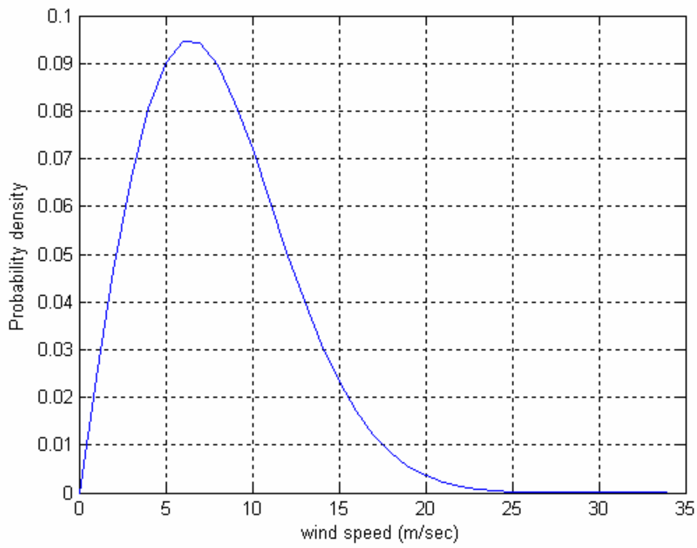

Figure 5.5: Rayleigh distribution for an average wind speed of 8 m/sec

The average wind power produced by the wind farm can be calculated as:

$$\mathrm{P}_{\mathrm{avg}} = \int_{w_{cin}}^{w_{cout}} P(w) \cdot R(w) dw \qquad \text{(Eq: 5.12)}$$

Where:
w_{cin} and w_{cout} : the cut in and cut out speed of the wind farm respectively,
$P(w)$: the power produced by the wind farm for wind speed *w,*
$R(w)$: the probability of a wind speed *w* occurring, according to the Rayleigh distribution

For the average wind speed of 8 m/sec and the wind farm of 700 MW rated power we find that the average power produced is:

$$\mathrm{P}_{\mathrm{avg}} = 333.9 MW$$

The same two parallel poles transmission system of the previous example will be examined. Again the same four modes of operation with the same probabilities will exist (Table 5.3). The assumption that the transmission line is operated for time *t* is made. The unavailability of the two parallel poles (AC-E not included) is given by:

$$Un_{pole1\&2} = \frac{Energy \quad not \quad transmitted}{Energy \quad that \quad could \quad have \quad been \quad transmitted} \qquad \text{(Eq: 5.13)}$$

Without any forced outages the total energy delivered during time *t* would have been:

$$E_{tot} = \mathrm{P}_{\mathrm{avg}} \cdot t = 333.9 \cdot t \text{ MWh.}$$

Each mode shall be examined separately:

- During mode 1 (96.785% of *t*): All the produced power is being transmitted
- During mode 4 (0.0262% of *t*): No power of the $\mathrm{P}_{\mathrm{avg}}$ produced is being transmitted
- During mode 2 (1.59% of *t*): For power production up to 500 MW all the power is being transmitted. What happens though if the produced power is above that limit? If it is assumed that the produced power is *y MW,* where y is greater than 500, then the non transmitted power will be (*y*-500) MW. According to the Rayleigh distribution and the aggregated model of the wind farm there is a very specific probability that *y* MW will be produced by the wind farm. This probability is named F(y). So if the transmission system operated continuously in this mode, the average value of the non transmitted power would be

$$P_{non\_tr\_mode2} = \int_{500}^{700} (y-500)F(y)dy \text{ MW} \qquad \text{(Eq: 5.14)}$$

$$P_{non\_tr\_mode2} = 53.3954 \text{ MW}$$

So for the 1.59% of t that actually mode 2 appears, the non-transmitted energy is:

$$53.3954 \cdot 0.0159 \cdot t = 0.849 \cdot t \text{ MWh}$$

- During mode 3 (1.59% of t): The same procedure as in mode 2 is followed. The result is:

$$P_{non\_tr\_mode3} = \int_{250}^{700} (y-250)F(y)dy = 158.7643 \text{ MW} \quad \text{(Eq: 5.15)}$$

The non-transmitted energy in this case is:

$$158.7643 \cdot 0.016696 \cdot t = 2.5244 \cdot t \quad \text{MWh}$$

For the system of the two parallel poles (without the AC filters) the total unavailability according to equation 5.13 will be:

$$Un_{p1\_p2} = \frac{0.96785 \cdot t \cdot 0 + 0.849 \cdot t + 2.5244 \cdot t + 0.000262 \cdot t \cdot 333.9}{333.9 \cdot t} \quad \text{(Eq: 5.16)}$$

$$Un_{p1\_p2} = 0.0104$$

Including the common AC-E (AC filters) the unavailability of the total system will be:

$$Un_{Tot} = Un_{pole1\&2} + Un_{AC-E} = 0.0104 + 0.001397 = 0.01179$$

$$\text{or } Un_{Tot} = 1.179\%$$

In the table bellow the energy unavailability of the system for different transmission lengths is presented:

Transmission Distance (km)	50	100	150	200	250	300
Unavailability (%)	1.0345	1.1787	1.3232	1.4681	1.6134	1.7590

Table 5.5: Energy Unavailability of the system described in Figure 5.3 for different transmission lengths. Windfarm rated at 700 MW as power input. 8m/sec average wind speed.

The same procedure is followed for all HVDC LCC transmission systems that were presented in section 4.3. The results concerning the percentage of energy not transmitted due to forced outages as well as the absolute value of the annually non-transmitted energy are given in detail in Appendix A.

5.2.4 Observations Concerning the Availability of HVDC LCC Transmission Systems

It is very important to note some of the characteristics that influence the availability of the transmission system based on observations of the results of the method introduced in the previous section. Generally the availability of the transmission system will increase as the number of parallel poles used increases. This happens because even when one pole is not operating due to a failure, a part of the produced power is still being transmitted through the remaining pole(s). An example of this case is shown in Table 5.6.

900 MW rated Windfarm						
Transmission Distance (km)	50	100	150	200	250	300
	8m/sec average wind speed					
3x 300 MW Parallel Poles						
Unavailability (%)	0.9504	1.0811	1.2121	1.3435	1.4753	1.6074
600 MW & 300 MW Parallel Poles						
Unavailability (%)	1.1116	1.2679	1.4245	1.5814	1.7386	1.8962

Table 5.6: Energy Unavailability comparison for two solutions of HVDC LCC transmission systems for the case of 900 MW windfarm. Average wind speed at 8 m/s. The first system uses three parallel poles while the second two.

Overrating a transmission system, that uses multiple parallel poles, will increase the total availability. A characteristic example of this case is presented in Table 5.7.

1000 MW rated Windfarm						
Transmission Distance (km)	50	100	150	200	250	300
8m/sec average wind speed						
2x 500 MW Parallel Poles						
Unavailability (%)	1.0656	1.2147	1.3641	1.5139	1.6640	1.8144
500 MW & 600 MW Parallel Poles						
Unavailability (%)	0.9468	1.0773	1.2081	1.3394	1.4711	1.6032
600 MW & 600 MW Parallel Poles						
Unavailability (%)	0.8280	0.9398	1.0521	1.1649	1.2782	1.3920

Table 5.7: Energy Unavailability comparison for three solutions of HVDC LCC transmission systems for the case of 1000 MW windfarm. Average wind speed at 8 m/s.

As it can be observed in Table 5.7, in the overrated transmission systems, when a fault occurs in one of the two poles, the operating pole not only continues to transmit half the amount of power from the wind farm but also a fraction of the power that was transmitted by the other pole before the fault. Thus the more the system is overrated the less is the effect of the forced outage on the system's availability.

700 MW rated Windfarm						
Transmission Distance (km)	50	100	150	200	250	300
8m/sec average wind speed						
500 MW & 250 MW Parallel Poles						
Unavailability (%)	1.0345	1.1787	1.3232	1.4681	1.6134	1.7590
440 MW & 300 MW Parallel Poles						
Unavailability (%)	1.0141	1.1551	1.2964	1.4382	1.5803	1.7228

Table 5.8:Energy Unavailability comparison for two solutions of HVDC LCC transmission systems for the case of 700 MW windfarm. Average wind speed at 8 m/s.

In systems that have the same number of parallel poles, the system that would have better availability in the one in which the transmission capability is more uniformally distributed among its parallel poles. A characteristic example is given in

Table 5.8 in which two solutions for transmission from a 700 MW windfarm are presented. Even though the first system (500 MW & 250 MW) has totally a larger transmission capability than the second (440 MW & 300 MW), the availability of the second system is higher.

In transmission systems that constitute of a single pole the availability does not depend on the input power or the possibility that this system might be overrated. This is more obvious by observing Equation 5.6. Examples of single pole transmission systems are presented in Table 5.9. In this table it can be noticed that all monopolar transmission system appear to have the same availability no matter the average wind speed or the rated power of the system.

Transmission Distance (km)	50	100	150	200	250	300
8,9,10,11 m/sec average wind speed						
400 MW Rated Windfarm						
440 MW Single Pole						
Unavailability (%)	1.5370	1.7601	1.9832	2.2063	2.4294	2.6525
500 MW Rated Windfarm						
500 MW Single Pole						
Unavailability (%)	1.5370	1.7601	1.9832	2.2063	2.4294	2.6525
600 MW Rated Windfarm						
600 MW Single Pole						
Unavailability (%)	1.5370	1.7601	1.9832	2.2063	2.4294	2.6525

Table 5.9: Energy Unavailability comparison for three single pole solutions of HVDC LCC transmission systems for the cases of 400 MW, 500 MW and 600 MW windfarms. Average wind speed at 8, 9 10 and 11 m/s.

5.3 HVDC VSC Transmission Systems Energy Availability

HVDC VSC transmission is a rather new technology and unlike HVDC LCC systems where statistical data concerning failures and reliability have been collected and analyzed for many years, no similar procedure exists for the HVDC VSC technology. In order to evaluate the availability of HVDC VSC transmission systems many assumptions had to be made. The first assumption was that only basic components of the transmission system, such as the converter transformers, the VSC units, the cable pair and circuit breakers were included. Many of the internal components of a converter station that were listed in Chapter 2 were ignored. The simplified model that was used for the evaluation of HVDC VSC transmission systems is shown in Figure 5.6.

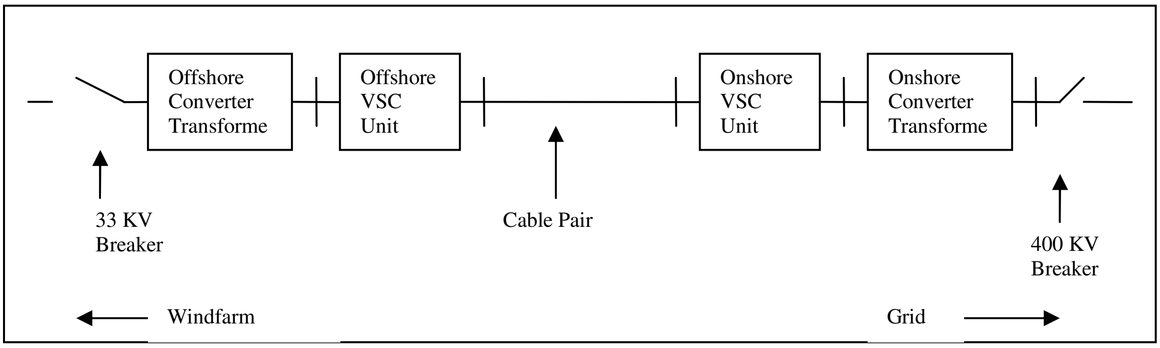

Figure 5.6: Simplified model used for the evaluation of HVDC VSC transmission system availability

In order to calculate the availability of the entire transmission system the availability of each component has to be known. The statistical data used in order to calculate the failure rate and thus the availability of each component were taken from the "Canadian Electricity Association" report on forced outage performance of transmission equipment [5.12]. In this report though, no data concerning HVDC VSC transmission systems exist. For the converter transformer, data for three phase high voltage transformers used in AC transmission systems were utilized. As for the VSC units, data for static compensators were used in order to calculate the availability. Since no data for large Voltage Source Converters exist, STATCOMs provide the closest solution because of the technological similarities that they appear to have with VSCs.

Another problem that was encountered was the lack of data concerning submarine DC cables with polymeric insulation that are used in HVDC VSC transmission systems. For this reason the unavailability calculated in Section 5.2 for submarine DC cables with mass impregnated insulation was used. This type of cables is used in HVDC LCC transmission systems. The forced outage data and the unavailability of the components described in the model of Figure 5.6 and were acquired from [5.12], are given in Tables 5.10, 5.11, 5.12 for several voltage levels.

As it can be observed from Table 5.10 for the voltage level of 150-199 kV an unusual high value of unavailability appears. The relatively small number of component years in this category combined with the probability of having defective material installed can provide a good explanation for this anomaly. Due to this, the transformer data that is used in the calculation of the total transmission system unavailability are taken from the 110-149 kV voltage level.

Transformer Banks	Number of Outages	Total duration (hrs)	Average duration (hrs)	Failure Rate (per year)	Unavailability (%)	Component years
110-149 kV	1443	257020	178.11	0.1756	0.3571	8215
150-199 kV	123	89712	729.36	0.3892	3.2408	316
200-299 kV	777	115514	148.66	0.1449	0.2460	5360
300-399 kV	164	33027	201.38	0.1324	0.3045	1238

Table 5.10: Statistical data concerning forced outages and energy availability for Transformer Banks for several voltage levels (source [5.12]).

The data for all voltage levels from Table 5.11 is used for the calculation of the system's availability, representing the unavailability of the VSC units. If the unavailability of the VSC units is compared to the one of the thyristor valves in the case of LCC systems (Table 5.1), one can observe that VSC units have lower reliability. This fact will have a significant effect in the energy availability of HVDC VSC transmission systems and thus to their transmission cost as it will be obvious later in this study.

STATCOMs	Number of Outages	Total duration (hrs)	Average duration (hrs)	Failure Rate (per year)	Unavailability (%)	Component years
Up to 109 kV	237	22281	94.01	3.31	3.55	71.5
110-149 kV	7	194	27.71	1.16	1.16	6
All voltage levels	244	22475	92.11	3.14	3.31	77.5

Table 5.11: Statistical data concerning forced outages and energy availability for Static Compensators for several voltage levels (source [5.12]). The data include subcomponents and all terminal equipment failures

In Table 5.12 the data concerning the circuit breakers are presented. The data are for all interrupting media breakers and include failures in all integral subcomponents and all terminal equipment. The voltage levels that are used in this study, as it can be seen from Figure 5.6, are the “300-399 kV” representing the 400 kV breaker and the “up to 109 kV” representing the 33 kV breaker.

Circuit Breakers (all media)	Number of Outages	Total duration (hrs)	Average duration (hrs)	Failure Rate (per year)	Unavailability (%)	Component years
Up to 109 kV	1304	430969	330.49	0.1221	0.4608	10675.5
110-149 kV	1659	286449	172.66	0.0919	0.1811	18049.5
150-199 kV	89	24663	277.11	0.0444	0.1407	2000.5
200-299 kV	1313	173186	131.90	0.1256	0.1892	10447.5
300-399 kV	505	53410	105.76	0.1181	0.1426	4275

Table 5.12: Statistical data concerning forced outages and energy availability for Circuit Breakers for several voltage levels (source [5.12]). The data are for all interrupting media and include subcomponents and all terminal equipment failures.

A summary of the unavailability of the components used in order to calculate the energy availability of HVDC VSC transmission systems is presented in Table 5.13.

	Offshore Converter Transformer	Onshore Converter Transformer	VSC Unit	33 kV Breaker	400 kV breaker	Submarine Cable Pair(1)
Unavailability (%)	0.3571	0.3045	3.3105	0.4608	0.1426	0.8924

(1) Per 100km

Table 5.13: Average time unavailability for each component of a HVDC VSC transmission system

In HVDC VSC technology both cables are necessary for the power transmission, thus when a fault occurs in one of them the operation of the transmission system is halted. For this reason the unavailability of the submarine cable pair, in Table 5.13, is twice as much the one of the submarine cable for HVDC LCC systems (Table 5.1).

5.3.1 Method for Calculating HVDC VSC Transmission Systems Unavailability

In order to calculate the energy unavailability of a HVDC VSC transmission system, namely the percentage of the input energy non-transmitted due to forced outages, the same procedure that was explained in Section 5.2.2 for HVDC LCC systems is followed. All the results concerning the percentage of energy not transmitted due to forced outages as well as the absolute value of the annually non-transmitted energy are given in detail in Appendix B. Following, some characteristic examples will be presented in order to justify the conclusions derived in Section 5.2.3, concerning the parameters that influence the energy availability of a transmission system.

In Table 5.14 two cases of HVDC SVC transmission schemes are presented. In the first case, two parallel lines transmit the power produced from a 500 MW windfarm. The second transmission scheme is a single HVDC SVC system. As it can be observed, the percentage of the non-transmitted power is much higher in the case of the single transmission line. As it was mentioned before, this is due to the fact that when a fault occurs in one transmission line a part of the produced power is being transmitted by the remaining one, when multiple transmission lines exist.

500 MW rated Windfarm						
Transmission Distance (km)	50	100	150	200	250	300
8m/sec average wind speed						
350+220 MW CS, 350+220 MW CP						
Unavailability (%)	4.9799	5.2638	5.5494	5.8368	6.1259	6.4167
1x500 MW CS,1x500 MW CP						
Unavailability (%)	8.3322	8.7784	9.2246	9.6708	10.1170	10.5632

Table 5.14: Energy Unavailability comparison for two solutions of HVDC VSC transmission systems for the case of 500 MW windfarm. Average wind speed at 8 m/s. CS: Converter Station, CP: Cable Pair.

When a transmission system, that uses more then one parallel lines, is overrated, the total energy availability of the system increases. This case is shown in Table 5.15 where the same transmission system, rated at 1000 MW, is used in two cases of windfarm rated power, 900 MW and 1000 MW respectively. In the case of the 900 MW windfarm the transmission system is overrated by 100 MW while in the case of the 1000 MW windfarm the transmission system is rated exactly to the power of the windfarm. It can be seen that the amount of the non-transmitted energy is smaller when the transmission system is overrated

Transmission Distance (km)	50	100	150	200	250	300
8 m/sec average wind speed						
900 MW Rated Windfarm						
2x500 MW CS, 2x500 MW CP						
Unavailability (%)	5.0030	5.2880	5.5747	5.8632	6.1534	6.4453
1000 MW Rated Windfarm						
2x500 MW CS, 2x500 MW CP						
Unavailability (%)	5.7191	6.0388	6.3598	6.6822	7.0060	7.3311

Table 5.15: Energy Unavailability comparison for the same HVDC VSC transmission system for the case of 900 MW and 1000 MW windfarm. Average wind speed at 8 m/s. CS: Converter Station, CP: Cable Pair.

In transmission systems that have the same number of parallel lines, better energy availability would appear in the system of which the transmission capability is more uniformally distributed among its parallel lines. This case is shown in Table 5.16.

700 MW rated Windfarm						
Transmission Distance (km)	50	100	150	200	250	300
8m/sec average wind speed						
2x350 MW CS, 2x350 MW CP						
Unavailability (%)	5.7515	6.0728	6.3953	6.7193	7.0445	7.3712
500+220 MW CS, 500+220 MW CP						
Unavailability (%)	5.9138	6.2429	6.5733	6.9049	7.2378	7.5719

Table 5.16: Energy Unavailability comparison for two solutions of HVDC VSC transmission systems for the case of 700 MW windfarm. Average wind speed at 8 m/s. CS: Converter Station, CP: Cable Pair.

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In transmission systems that constitute of a single line the availability does not depend on the input power or the possibility that this system might be overrated. An example of a single line transmission system is presented in Table 5.17. In this table it can be noticed that the single line transmission system, rated at 500 MW, appears to have the same availability no matter the average wind speed even though the windfarm is of smaller rated power.

400 MW rated Windfarm						
Transmission Distance (km)	50	100	150	200	250	300
8, 9, 10, 11m/sec average wind speed						
500 MW CS, 1x500 MW CP						
Unavailability (%)	8.3322	8.7784	9.2246	9.6708	10.1170	10.5632

Table 5.17: Energy Unavailability of a single line HVDC VSC transmission system for the case of 400 MW windfarm. Average wind speed at 8, 9, 10, 11 m/s. CS: Converter Station, CP: Cable Pair

5.4 HVAC Transmission Systems Energy Availability

The first two steps in order to evaluate the energy availability for a HVAC transmission system is to model the standardized layout of the transmission system upon which the algorithm is going to be applied and to define the unavailability of each component included in this model. The simplified model that defines the layout of a HVAC transmission system from an offshore windfarm is shown in Figure 5.7. The figure below represents a case of a HVAC transmission system that uses two submarine XLPE cables. As it was mentioned before three transmission voltage levels are considered in this study, 132 kV, 220 kV and 400 kV. In case of a 400 kV transmission voltage the offshore transformer and the breaker between the offshore transformer and the cable(s) are not required.

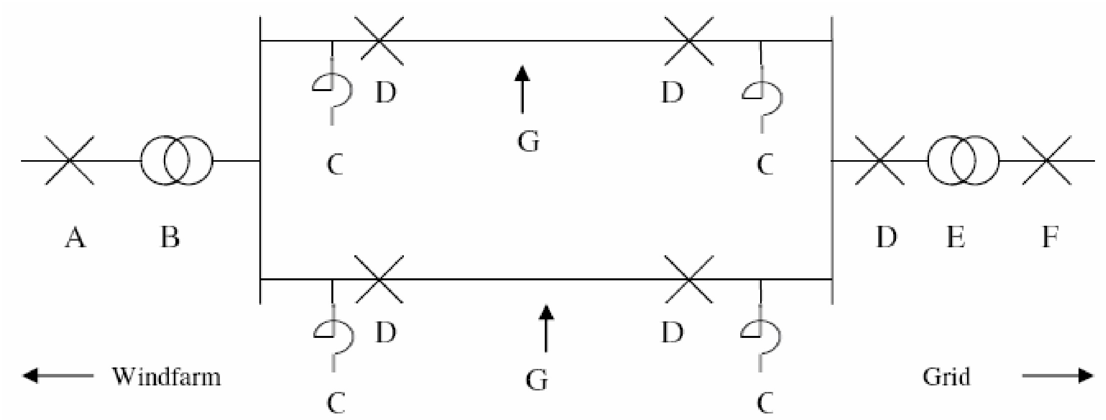

Figure 5.7: Simplified model used for the evaluation of HVAC transmission systems energy availability. A: circuit breaker (33 kV), B: offshore transformer (33kV/transmission voltage), C: shunt reactor, D: Circuit breaker (transmission voltage), E: Onshore transformer (transmission voltage/400 kV), F: circuit breaker (400 kV), G: Three core XLPE submarine cable (transmission voltage)

The statistical data used in order to calculate the failure rate and the availability of each component were taken again from the "Canadian Electricity Association" report on forced outage performance of transmission equipment [5.12].

The data for transformer banks are given in Table 5.10. For 132 kV transformers the statistics come from the "110-149 kV" category, for 220 kV transformers from the "200-299 kV" category and finally for the 400 kV transformers from the "300-399 kV" category. The statistics for circuit breakers are presented in Table 5.12. Again depending on the transmission voltage the corresponding voltage level in Table 5.12 was chosen. The statistics for the shunt reactor are given in Table 5.18, are for all voltage levels and include failures in all integral components and terminal equipment.

Shunt Reactor Bank	Number of Outages	Total duration (hrs)	Average duration (hrs)	Failure Rate (per year)	Unavailability (%)	Component years
All voltage levels	36	2395	66.52	0.0923	0.0701	390

Table 5.18: Statistical data concerning forced outages and energy availability for Shunt Reactor Banks for all voltage levels (source [5.12]). The data include subcomponents and all terminal equipment failures

A problem encountered was the lack of data concerning three-core, submarine, XLPE cables. For this reason, as it was done in the HVDC VSC case, the unavailability of the AC cables for all voltage levels was considered to be the same as the one calculated for mass impregnated DC cables. A summary of the unavailability of the components used in order to evaluate the energy availability of the HVAC transmission schemes is given in Table 5.19.

Unavailability (%)		Transformers	Breakers	Shunt Reactors	Cables(1)
Voltage level (kV)	33	-	0.4608	-	-
	132	0.3571	0.1811	0.0701	0.4462
	220	0.2460	0.1892	0.0701	0.4462
	400	0.3045	0.1426	0.0701	0.4462

(1) Per 100km

Table 5.19: Average time unavailability for each component of a HVAC transmission system.

5.4.1 Method for Calculating HVAC Transmission Systems Energy Availability

In the energy availability study of HVDC transmission systems several cases of parallel transmission lines were examined. The parallel poles constituted a transmission system of multiple, independent of each other, transmission lines. In case a failure occurred in a line, the other lines could transmit a part of the power that previously was directed through the one that failed. In HVAC transmission systems the offshore transformers have their high voltage side connected to a common bus. All the cables have their offshore ends connected to this bus. The same is observed at the onshore side of the transmission system. In other words in a HVAC transmission system a pair of transformers is not connected to a single cable, thus the transmission system does not constitute of parallel independent transmission lines. This situation, combined with the fact that most of the HVAC layouts chosen by Todorovic [5.13] (Table 4.1) use multiple offshore and onshore transformers as well as multiple cables, made the calculation of the energy availability for the chosen HVAC transmission systems more complex. Figure 5.8 presents the chosen by Todorovic [5.13] solution for transmission from a 900 MW windfarm for the voltage level of 220 kV and a transmission distance of 50 km.

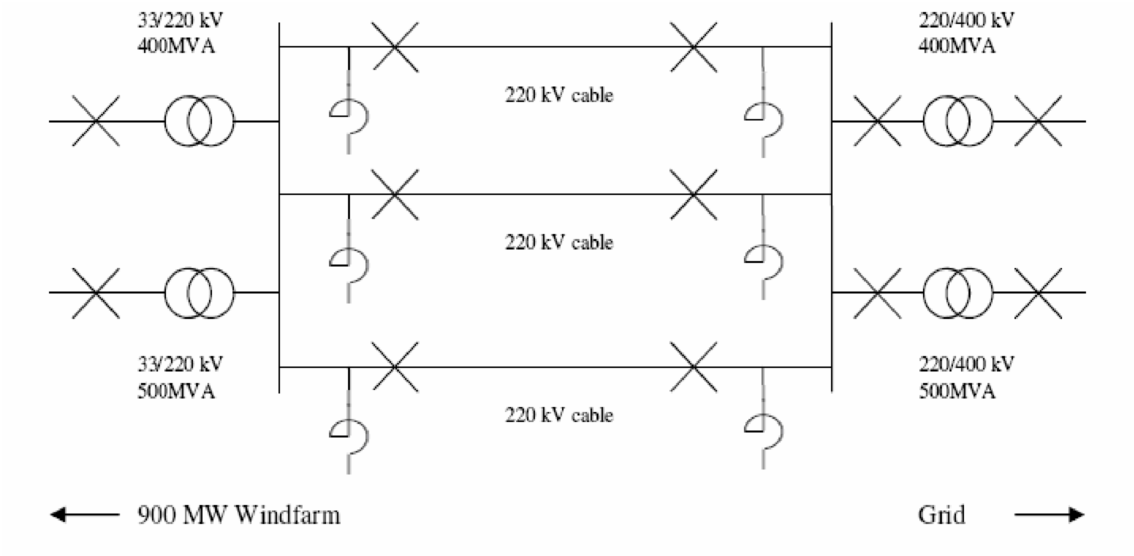

Figure 5.8: HVAC transmission system from a 900 MW offshore windfarm. Voltage level 220 kV, transmission distance 50 km.

As it can be observed, there are two common buses where the two ends of the cables are connected to the offshore and onshore transformers respectively. All cables can be fed through the common bus by every offshore transformer.

In order to calculate the above system's energy availability the following assumption have to be made:

- Each offshore transformer and the serial to it connected breaker are considered as one component. The total unavailability (probability of not operating for a specific period of time) is the sum of the individual unavailability values in accordance to the method followed in Section 5.2.2, Equation 5.5.
- Each cable, the two shunt reactors and the two circuit breakers connected to it are considered as one component. The total unavailability (probability of not operating for a specific period of time) is the sum of the individual unavailability values in accordance to the method followed in Section 5.2.2, Equation 5.5.
- Each onshore transformer and the two circuit breakers connected to its primary and secondary side again are considered as one component with total unavailability the sum of the individual unavailability values.

Next, the different operation modes of the system have to be extracted together with the probability of each mode and its power transmission capability as shown for the HVDC LCC case in Table 5.3. For this reason, all the possible combinations in the transmission system concerning the operation states (operating or not) of the three major components mentioned above, have to be enumerated. The conclusion of this procedure is a table in the form of Table 5.3, but much more extended. The final step for the calculation of the entire system's energy availability is to follow the procedure of the third case of Section 5.2.2, namely to use a windfarm as an input to the transmission system.

5.4.2 HVAC Transmission System's Energy Availability Results

Following the method described in the previous section, the energy availability of all the HVAC transmission systems listed in Table 4.1 is calculated. All the results for the HVAC transmission systems chosen by Todorovic [5.13] plus the modified systems presented in Section 4.2.1 are given in Appendix C. There are some interesting facts worth of noticing concerning characteristics of HVAC transmission systems. Unlike HVDC systems were the number of cables does not depend on the transmission distance, in HVAC systems the number of cables increases with increasing transmission distance, depending on the transmission voltage and the transmission capacity of the specific cable (see Figure 4.1). For this reason, in many cases of HVAC systems a decrease of the unavailability is observed with increasing distance. A characteristic example of this situation is presented in Table 5.20.

800 MW rated Windfarm						
Transmission Distance (km)	50	100	150	200	250	300
8m/sec average wind speed						
Transmission Voltage: 132 kV						
Unavailability (%)	1.0980	1.1888	1.3553	1.6620	1.3987	1.5799
Transmission Voltage: 220 kV						
Unavailability (%)	0.8936	0.9574	1.1433	1.5670	1.1817	-

Table 5.20: Energy Unavailability for 132 kV and 220 kV HVAC transmission systems for a windfarm rated at 800 MW. Wind average speed 8m/s.

For the 132 kV system of Table 5.20 a decrease of the unavailability is observed for the transition from 200 km to 250 km transmission distance. This is due to the fact that for 200 km four 132 kV cables are used, while for 250 the need is for five 132 kV cables (see Table 4.1). The same is observed for the 400 kV case for the transition from 200 to 250 km.

As it was mentioned for the chosen HVDC transmission schemes, overrated systems have the tendency to present much better availability compared with systems with power capacity very close to the rated power of the wind farm. In HVAC systems this phenomenon is better observed in a comparison between the modified systems and the corresponding original ones chosen by Todorovic. In Table 5.21 one of these cases is being presented.

Wind speed	8 m/s	9 m/s	10 m/s	11m/s
800 MW windfarm, 2x 400 kV cables, 100 km transmission distance				
Unavailability (%)	0.6599	0.7099	0.7467	0.7740
795 MW windfarm, 1x 400 kV cable, 100 km transmission distance				
Unavailability (%)	1.5134	1.5622	1.5982	1.6248

Table 5.21: Energy Unavailability comparison of two HVAC transmission systems from 800 and 795 MW windfarms respectively for several average wind speeds. Transmission Voltage: 400 kV, Transmission distance 100km.

A 400 kV cable at 100 km transmission distance, with compensation at both ends, has a power transmission capacity of almost 795 MW. Thus, the second transmission system in Table 5.21 has a cable rated at a value very close to the one required. On the other hand, the first transmission system has two cables with total transmission capacity almost twice as much the required one. Even though the case for the first transmission system is not realistic, it provides a good example for comparison of the energy availability between overrated and exactly rated transmission systems.

In the method used for the calculation of the energy availability the losses of the transmission line were ignored. In HVDC transmission systems, where the losses in most cases are bellow 5%, the effect of this assumption in the final result is minor. In HVAC systems though, as it can be seen from Tables 4.3, 4.4 and 4.5 the losses in some cases can reach up to 20% of the average input power, mainly for transmission systems from large windfarms and for large transmission distances . In these cases it should be expected that the unavailability of the transmission system should have smaller value compared to the ones given in Appendix C. This small deviation from the actual result has a very small impact on the final analysis of the cost of transmission. It will be obvious later that the transmission cost for these HVAC systems is so high that a small decrease in the unavailability, in the order of some decimals, does not have a great effect on the final result.

5.5 Comparison of Energy Unavailability for Transmission from a 1000 MW Windfarm

In this section, the results concerning the energy availability of two transmission systems, one of HVDC LCC technology and one of HVDC VSC technology, for a windfarm size of 1000 MW will be compared. Both transmission systems constitute of two 500 MW converters in parallel. If the results in Appendix A and B are examined, one can observe that these two configurations do not provide the best choices in terms of energy availability. The choice of the specific systems was made upon the fact that their rated power is the same and equal to the rated power of the windfarm and their layout is similar. This way, specific conclusions can be drawn concerning their energy availability performance. The HVAC transmission systems presented in this study are in many cases overrated and especially for long transmission distances do not provide realistic solutions (losses that can exceed 15%, use of many cables because of the reactive power saturation and thus great cost). For the reasons mentioned above, the specific HVAC solutions cannot provide a good comparable example and thus are not included.

Energy Availability (%)	**HVDC LCC : 2x500 MW converter station HVDC VSC: 2x500 MW converter station, 2x500 MW cable pair**							
Transmission Distance	8 m/s		9 m/s		10 m/s		11 m/s	
	LCC	VSC	LCC	VSC	LCC	VSC	LCC	VSC
50 km	1.0656	5.7191	1.1555	6.2174	1.2215	6.5830	1.2700	6.8522
100 km	1.2147	6.0388	1.3187	6.5612	1.3950	6.9445	1.4512	7.2267
150 km	1.3641	6.3598	1.4822	6.9061	1.5688	7.3069	1.6326	7.6020
200 km	1.5139	6.6822	1.6459	7.2521	1.7428	7.6702	1.8141	7.9781
250 km	1.6640	7.0060	1.8099	7.5992	1.9170	8.0345	1.9959	8.3550
300 km	1.8144	7.3311	1.9742	7.9474	2.0915	8.3996	2.1778	8.7326

Table 5.22: Energy availability comparison between one HVDC LCC and one HVDC VSC transmission systems for the case of 1000 MW windfarm

As it can be observed from Table 5.22 HVDC VSC systems have much higher energy unavailability compared to HVDC LCC transmission systems. There are two major factors that lead to this result:

- The much higher unavailability value for Voltage Source Converters (VSC) used in this study compared to value for Line Commutated Converters.
- The value of the unavailability for the interconnecting cable pair in the VSC cases is twice as much the value of the unavailability for the interconnecting cable in LCC cases.

5.6 Summary

The energy availability can be considered as a measure of the efficiency and the reliability of a transmission system. In this chapter some ways of increasing the energy availability have been indicated such as including multiple parallel poles and lines. Overrating those parallel poles will even more improve the energy availability. It has to be noted though that every effort to increase the energy availability will lead to an increase of the investment cost. It is thus very important to find the combination of cost, availability and losses that will provide the best economical solution. The algorithm that was described in this chapter provides an evaluation of the energy unavailability of all the transmission systems that were described in previous chapters. Based on the fact that these transmission systems have windfarms as inputs, the Rayleigh distribution of the wind speed and the aggregated power curve of the windfarm were included in this algorithm. The results from the energy availability study made in this chapter will be important parameters in the final economical comparison of the several transmission systems.

5.7 References and Sources

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6

Energy Transmission Cost

6.1 Introduction

The final step in this study is the evaluation of the transmission cost for every transmission system that has been introduced so far. In this Chapter the economic model used in order to evaluate the transmission will be introduced. Besides the losses and the energy availability that have already been presented, the investment cost for the transmission systems is given. The cost of each component and the assumptions made in many cases will be presented. Finally, comparisons between the costs of transmission of the several technologies will be made in order for some interesting results to be extracted.

6.2 Cost of the Components of the Transmission Systems

The most difficult part for the completion of this study was the lack of data concerning the cost of the several components of the three transmission technologies that are under investigation. This is due to the fact the related industry treats this kind of information as confidential. However an effort to be as accurate as possible was made and in all cases of cost related matters the references are given.

It should be noted that all prices presented in this chapter are given in Euros. All prices that were found in another currency were converted to Euros using the exchange rate of November 2004. Also, prices that were referring to previous years were converted to 2004 prices using an annual inflation rate of 2%.

6.2.1 HVDC LCC Cost of Components

One of the latest HVDC LCC interconnections built, that also uses submarine cable transmission, is the one between Greece and Italy (2002). According to [6.1] each one of the two 500 MVA converter stations had an approximate cost of 40 million Euros, giving a price of 0.08 €/VA. This price will be used as input to all the cases that Barberis [6.5] suggests. As for submarine, mass impregnated, DC cables the following cost were detected, as shown in Table 6.1. In the prices listed in this table the laying cost of the cables are included.

Cable capacity (MW)	Project Name	Price in year of completion (or study)	Price in 2004	source
600	SwePol link	860.000 €/km (2002)	900.000 €/km	[6.2]
550	Iceland link(3)	820.000 $/km (1999)	724.000 €/km	[6.3]
500	ItalGre link	660.000 €/km (2002)	700.000 €/km	[6.2]
440	Skagerrak 3 link	170 M $ (1993)(1)	700.000 €/km(2)	[6.4]

(1) Price for the entire project, (2) price only for the cable, (3) project proposal

Table 6.1: DC cable cost according to power capacity and references.

Using the prices listed in Table 6.1, a linear model that will be used to define the cost for every case of cables used for the recommended HVDC LCC transmission systems is extracted. The model is presented in Figure 6.1 and has the following mathematical expression:

$$Cost = 1.148P + 156.1 \qquad \text{(Eq. 6.1)}$$

where *Cost* is the cost of the cable per km (including installation) in thousands of Euros and *P* is the power capacity of the cable in MW.

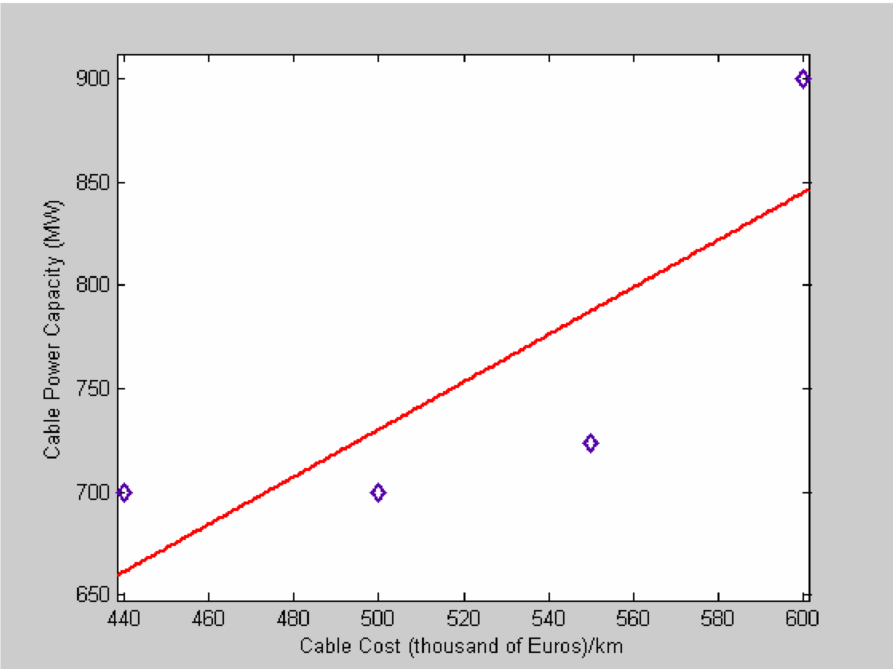

Figure 6.1: Linear model defining the cost of cables depending on the power capacity. Diamonds indicate real cases.

According to the linear model of Equation 6.1, the costs of buying and laying the cables for the HVDC LCC transmission schemes chosen by Barberis [6.5], are listed in Table 6.2.

MI cable rated Power (MW)	600	500	440	300	250	130
Cost/km (M€)	0.844	0.730	0.660	0.500	0.443	0.305

Table 6.2: Cost per km for the cables used in the HVDC LCC transmission systems of this study. Costs for laying the cables are included.

6.2.2 HVDC VSC Cost of Components

Several sources were examined in order to estimate the cost of the components composing a HVDC VSC transmission system, namely the converter station and whatever it includes (valves, transformers, filters etc) and the submarine DC cables. According to the cost data, provided in a technical report by ABB about HVDC VSC [6.6], the price of converter station for HVDC VSC technology is set to 0.11 €/VA. This value seems to be in agreement with the cost of 1 SEK/VA that Lundberg [6.7] suggests for the converters in his report.

For the cost of the DC cables used in HVDC VSC transmission systems the prices models that Lundberg [6.7] provides for DC cables where used. In the studied cases, namely the ones suggested by Barberis [6.5], three types of cables were used rated at 220, 350 and 500 MW respectively. All these cables have rated voltage of +- 150 kV. In Lunberg's model (also for +- 150 kV cables) the following formula is used:

$$Cost = 0.286 + 0.00969P \quad \text{(Eq. 6.2)}$$

In the formula above P is the rated power of the cable in MW, and $Cost$ is the cost only for purchasing the cable in MSEK. After applying the model to the three cables mentioned above and converting the cost to Euros the following results for the cable pairs are extracted as listed in Table 6.3.

Cable Rated power (MW)	220	350	500
Cost per cable pair (M€/km)	0.30377	0.4453	0.6086

Table 6.3: Cost per km for the cables used in the HVDC VSC transmission systems of this study. Costs for laying the cables are not included.

The cost for installing each cable is set to 100,000 €/km. The assumption made is that only one cable can be installed at a time thus for the cable pair the cost is set to 200,000 €/km.

According to the assumption made above concerning the cost of the components of HVDC VSC transmission systems, the cost for the "Cross-Sound" HVDC VSC link, which is rated at 350 MW and has a 50 km submarine cable pair, would be:

$$Cost_{total} = 2 \times (Cost_{Converter\_station}) + 50 \times (Cost_{cable\_pair} + Cost_{install}) \quad \text{(Eq 6.3) or}$$

$$Cost_{total} = 2 \cdot 350 \cdot 0.11 + 50 \cdot (0.4453 + 0.2) = 109.26 \text{ M€}$$

According to [6.8] the total cost for the "Cross-Sound Cable" HVDC link (2002) was 110 M€.

6.2.3 HVAC Cost of Components

Unlike HVDC solutions where the data on the cost of components was reduced in two major categories, namely the cost of the converter stations and the cost of cables (also the cost of cable installation for the HVDC VSC case), in HVAC transmission systems the list of components whose cost has to be defined is more extensive. To be more specific, costs of the following components have to be defined:

- Transformers
- Compensators
- 132 kV, 220 kV and 400 kV three-core, XLPE, submarine cables.
- Cables installation cost
- Switch gear

6.2.3.1 Cost of Transformers

A list of transformers costs is presented in Table 6.4 based on information derived from [6.9]. The cost of the transformers is according to their rated power.

Rated Power (MVA)	800	722	630	400	300	250	200	180	150	125	100	50	40
Cost (M€)	5.04	4.67	4.22	3.00	2.43	2.10	1.78	1.65	1.44	1.25	1.06	0.63	0.53

Table 6.4: Cost of Transformers according to their rated power (source [6.8])

The data from Table 6.4 are graphically represented in Figure 6.2 together with the fitting curve.

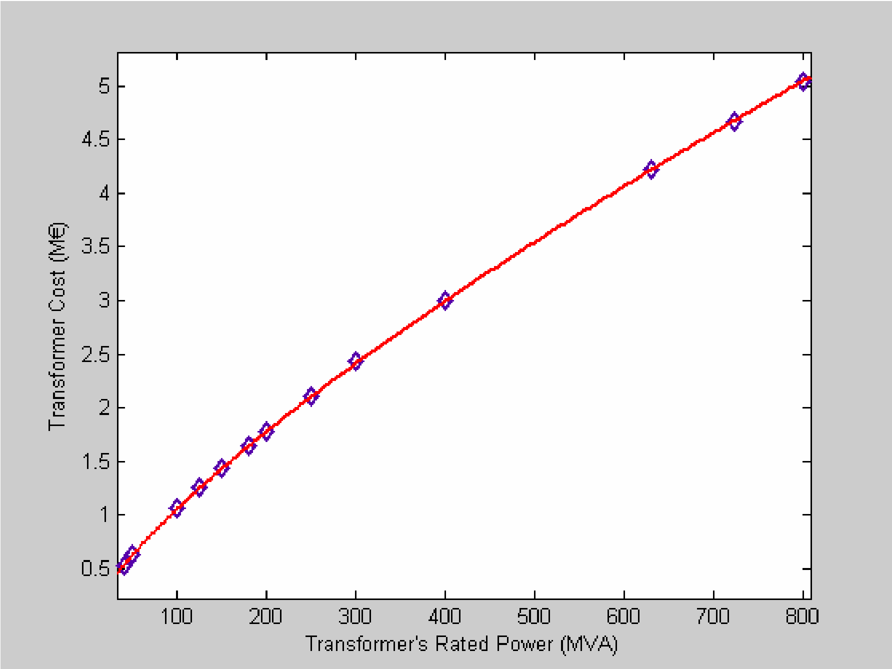

Figure 6.2: Fitting curve for cost of three phase transformer according to their rated power. Diamonds indicate real cases

The curve of Figure 6.2 is mathematically described by the following equation:

$$Cost_{trans} = 0.03327 \cdot P^{0.7513} \quad \text{(Eq. 6.4).}$$

Where:

$Cost_{trans}$ The cost of the transformer in M€

P The rated power of the transformer in MVA

Based on Equation 6.4 the cost for the transformers used in this study, as they were presented in Chapter 4, can be calculated. The results are given in Table 6.5.

Rated Power of Transformer (MVA)	300	400	500	600
Cost (M€)	2.43	3.00	3.54	4.06

Table 6.5: Cost of Transformers used in this study

6.2.3.2 Cost of Compensators

As it was mentioned in Chapter 4, reactive power compensation is essential for HVAC transmission. In Table 6.6 the required compensation in MVA required at each end of the AC cable, depending on the voltage level and the transmission distance, is presented once again.

MVA	Transmission Distance					
Transmission Voltage	50 km	100 km	150 km	200 km	250 km	300 km
132 kV	32.5	65	97.5	130	162.5	195
220 kV	71	142	213	284	355	-
400 kV	226	452	678	904	-	-

Table 6.6: Compensation needed (MVA) at each end of each cable installed according to the voltage level and the transmission distance.

For the cost of compensators the assumption that the price of compensators is the 2/3 of the price of the transformer with the same MVA rating (same assumption made by Lundberg [6.7]). Based on this and according to the cost model derived for the transformers (Equation 6.4) the cost for the compensators is calculated. The results are listed in Table 6.6.

132 kV						
Rating of compensator (MVA)	32.5	65	97.5	130	162.5	195
Cost (M€)	0.3033	0.5105	0.6923	0.8593	1.0162	1.1654
220 kV						
Rating of compensator (MVA)	71	142	213	284	355	
Cost (M€)	0.5455	0.9183	1.2453	1.5458	1.8279	
400 kV						
Rating of compensator (MVA)	226	452	678	904		
Cost (M€)	1.3020	2.1916	2.9721	3.6892		

Table 6.6: Cost of reactive power compensators used in this study

6.2.3.3 Cost of AC Cables

For the three-core XLPE cables the models provided by Lundberg [6.7] were used. The characteristics of the three cables used in this study, as they were presented in Chapter 4, are presented in Table 6.7.

Cable Rated Voltage (kV)	132	220	400
Rated current (A)	1055	1055	1323
Cross section (mm^2)	1000	1000	1200

Table 6.7: Characteristics of the three-core XLPE cables used in this study

According to Lundberg for the132 kV cable in Table 6.7 the cost is:

$$C_{132} = 1.971 + 0.209\exp(\frac{1.66S_n}{100}) = 13.4507 MSEK / km \quad \text{(Eq. 6.5)}$$

$$S_n = \sqrt{3} \cdot U_{rated} \cdot I_{rated} \quad \text{(Eq. 6.6)}$$

Also according to Lundberg the cost for the 220 kV cable is:

$$C_{220} = 3.181 + 0.11\exp(\frac{1.16S_n}{100}) = 14.8382 MSEK / km \quad \text{(Eq. 6.7)}$$

$$S_n = \sqrt{3} \cdot U_{rated} \cdot I_{rated}$$

After converting the above costs in Euros the results are:

$C_{132} = 1.5$ M€/km and $C_{220} = 1.65$ M€/km

The largest assumption made was concerning the cost of the 400 kV cables. As mentioned before three-core XLPE cables at this voltage level are still under development so no references related to their cost were detected. Thus the cost for the 400 kV cable, with the characteristics specified in Table 6.7, was set to 1.95 M€/km. This value can be considered more as a guess rather than an estimation.

The installation cost for the HVAC cables, as done for the HVDC VSC case, is considered to be 100,000 €/km. It is assumed that only one cable can be laid during one route of the cable installation vessel.

6.2.3.4 Cost of Switch Gear

For the switch gear cost also, the models provided by Lundberg [6.7] were used. For the four voltage levels of switch gear used in this study the costs are presented in Table 6.8.

Switch Gear rated Voltage (kV)	33	132	220	400
Cost (M€)	0.058	0.124	0.183	0.303

Table 6.6: Cost of switch gear used in this study

6.3 Method for Calculating the Energy Transmission Cost

The energy transmission cost is defined as how much it costs to deliver a unit of energy, produced by the windfarm, to the onshore grid. If it is assumed that the investment for constructing the transmission system is made today and it is paid off during the life time of the transmission system (i.e. 30 years), the total investment cost is given by:

$$C_{invest} = \frac{r(1+r)^N \cdot N}{(1+r)^N - 1} \cdot Invest \quad \text{(Eq. 6.8)}$$

Where:

Invest Investment paid today (€)

N Life time of the project (years)

r Interest rate (%)

C_{invest} Total investment paid off (€)

According to Equation 6.8, the annual instalment for such a loan will be:

$$R = \frac{r(1+r)^N}{(1+r)^N - 1} \cdot Invest \quad \text{(Eq. 6.9)}$$

Where:

R Investment annual instalment (€)

The amount of energy that is delivered to the onshore grid for an operation period of one year is given by:

$$E_D = P_{out,AVG} \cdot \left(1 - \frac{L}{100}\right) \cdot T \cdot \left(1 - \frac{U_n}{100}\right) \qquad \text{(Eq. 6.10)}$$

Where:

E_D The amount of energy delivered to the onshore grid (kWh)

$P_{out,AVG}$ The average power output from the windfarm (kW)

L The average power losses in the transmission system (%)

U_n The energy unavailability of the transmission system (%)

T The operational time of the windfarm under one year (hours)

If it assumed that the company that owns the transmission system has to make a profit p (in %) every year, then the energy transmission cost can be defined combining Equations 6.9 and 6.10 as:

$$C_{trans} = \frac{R}{E_D} \frac{100}{100 - p} \qquad \text{(Eq. 6.11)}$$

Where:

C_{trans} Energy transmission cost (€/kWh)

R Annual instalment for the investment (€)

E_D Energy delivered (kWh)

p Annual profit (%)

The life time N of the project is defined to be 30 years, the interest rate r 3%, the operational time T of the windfarm for one year $356 \cdot 24$ hours and the annual profit p 2%. The losses and the energy availability of each transmission system have been presented in Chapters 4 and 5 respectively. The investment cost for each transmission system can be calculated based on the description of the layouts given in Chapter 4 and the costs for each component presented in Section 6.2. Based on these, all of the inputs to the model of Equation 6.11 have been defined and thus the energy transmission cost can be calculated.

6.3.1 Energy Transmission Cost Results

In Tables 6.7 and 6.8 the lowest energy transmission costs for each transmission technology are presented. All the results are given in Appendix 6.1.

€/kWh	400 MW											
Transm. Length	HVAC				HVDC VSC				HVDC LCC			
	8 m/s	9m/s	10m/s	11m/s	8 m/s	9m/s	10m/s	11m/s	8 m/s	9m/s	10m/s	11m/s
50 km	0.0031	0.0027	0.0025	0.0023	0.0047	0.0041	0.0037	0.0035	0.0033	0.0029	0.0026	0.0024
100 km	0.0070	0.0060	0.0054	0.0050	0.0062	0.0054	0.0049	0.0045	0.0044	0.0038	0.0034	0.0032
150 km	0.0107	0.0093	0.0083	0.0077	0.0077	0.0067	0.0060	0.0056	0.0055	0.0048	0.0043	0.0040
200 km	0.0236	0.0205	0.0185	0.0172	0.0091	0.0080	0.0072	0.0067	0.0066	0.0057	0.0052	0.0048
250 km	0.0449	0.0389	0.0350	0.0324	0.0107	0.0093	0.0084	0.0078	0.0077	0.0067	0.0060	0.0056
300 km	0.0583	0.0505	0.0454	0.0421	0.0122	0.0106	0.0096	0.0089	0.0088	0.0077	0.0069	0.0064

€/kWh	500 MW											
Transm. Length	HVAC				HVDC VSC				HVDC LCC			
	8 m/s	9m/s	10m/s	11m/s	8 m/s	9m/s	10m/s	11m/s	8 m/s	9m/s	10m/s	11m/s
50 km	0.0028	0.0024	0.0022	0.0020	0.0043	0.0037	0.0033	0.0031	0.0030	0.0026	0.0023	0.0022
100 km	0.0056	0.0048	0.0044	0.0040	0.0055	0.0048	0.0043	0.0040	0.0040	0.0034	0.0031	0.0029
150 km	0.0085	0.0074	0.0066	0.0061	0.0067	0.0058	0.0052	0.0049	0.0049	0.0043	0.0039	0.0036
200 km	0.0210	0.0182	0.0163	0.0151	0.0080	0.0069	0.0062	0.0058	0.0059	0.0051	0.0046	0.0043
250 km	0.0366	0.0318	0.0287	0.0266	0.0092	0.0080	0.0072	0.0067	0.0069	0.0060	0.0054	0.0050
300 km	0.0616	0.0534	0.0480	0.0445	0.0105	0.0091	0.0082	0.0076	0.0079	0.0068	0.0062	0.0057

€/kWh	600 MW											
Transm. Length	HVAC				HVDC VSC				HVDC LCC			
	8 m/s	9m/s	10m/s	11m/s	8 m/s	9m/s	10m/s	11m/s	8 m/s	9m/s	10m/s	11m/s
50 km	0.0024	0.0021	0.0018	0.0017	0.0049	0.0042	0.0038	0.0036	0.0030	0.0026	0.0023	0.0021
100 km	0.0047	0.0040	0.0036	0.0034	0.0062	0.0054	0.0049	0.0045	0.0039	0.0034	0.0030	0.0028
150 km	0.0071	0.0062	0.0055	0.0051	0.0075	0.0065	0.0059	0.0055	0.0048	0.0042	0.0038	0.0035
200 km	0.0236	0.0205	0.0185	0.0172	0.0088	0.0077	0.0070	0.0065	0.0057	0.0050	0.0045	0.0042
250 km	0.0400	0.0347	0.0313	0.0290	0.0102	0.0089	0.0080	0.0075	0.0067	0.0058	0.0052	0.0048
300 km	0.0636	0.0552	0.0497	0.0460	0.0116	0.0101	0.0091	0.0085	0.0076	0.0066	0.0060	0.0055

€/kWh	700 MW											
Transm. Length	HVAC				HVDC VSC				HVDC LCC			
	8 m/s	9m/s	10m/s	11m/s	8 m/s	9m/s	10m/s	11m/s	8 m/s	9m/s	10m/s	11m/s
50 km	0.0020	0.0018	0.0016	0.0015	0.0042	0.0037	0.0033	0.0031	0.0032	0.0028	0.0025	0.0023
100 km	0.0040	0.0035	0.0031	0.0029	0.0054	0.0047	0.0042	0.0039	0.0042	0.0037	0.0033	0.0031
150 km	0.0112	0.0097	0.0088	0.0081	0.0065	0.0057	0.0051	0.0048	0.0053	0.0046	0.0042	0.0039
200 km	0.0224	0.0194	0.0174	0.0161	0.0077	0.0067	0.0061	0.0056	0.0064	0.0056	0.0050	0.0047
250 km	0.0348	0.0303	0.0274	0.0254	0.0089	0.0078	0.0070	0.0065	0.0075	0.0065	0.0059	0.0055
300 km	0.0550	0.0478	0.0431	0.0400	0.0101	0.0088	0.0080	0.0074	0.0086	0.0075	0.0067	0.0063

€/kWh	800 MW											
Transm. Length	HVAC				HVDC VSC				HVDC LCC			
	8 m/s	9m/s	10m/s	11m/s	8 m/s	9m/s	10m/s	11m/s	8 m/s	9m/s	10m/s	11m/s
50 km	0.0018	0.0016	0.0014	0.0013	0.0045	0.0039	0.0035	0.0033	0.0030	0.0026	0.0024	0.0022
100 km	0.0035	0.0031	0.0028	0.0026	0.0057	0.0050	0.0045	0.0042	0.0040	0.0035	0.0032	0.0029
150 km	0.0105	0.0091	0.0082	0.0076	0.0071	0.0062	0.0056	0.0052	0.0050	0.0044	0.0040	0.0037
200 km	0.0196	0.0170	0.0154	0.0142	0.0084	0.0073	0.0066	0.0062	0.0061	0.0053	0.0048	0.0044
250 km	0.0356	0.0308	0.0277	0.0256	0.0097	0.0085	0.0077	0.0072	0.0071	0.0062	0.0056	0.0052
300 km	0.0573	0.0498	0.0450	0.0417	0.0111	0.0097	0.0088	0.0082	0.0081	0.0071	0.0064	0.0059

Table 6.7: Lowest energy transmission costs for each transmission technology, windfarm size, average wind speed and transmission distance. Part One

€/kWh	900 MW											
	HVAC				HVDC VSC				HVDC LCC			
Transm. Length	8 m/s	9m/s	10m/s	11m/s	8 m/s	9m/s	10m/s	11m/s	8 m/s	9m/s	10m/s	11m/s
50 km	0.0016	0.0014	0.0013	0.0012	0.0044	0.0039	0.0035	0.0033	0.0030	0.0026	0.0024	0.0022
100 km	0.0061	0.0053	0.0048	0.0044	0.0058	0.0051	0.0046	0.0043	0.0040	0.0035	0.0031	0.0029
150 km	0.0093	0.0081	0.0073	0.0067	0.0071	0.0062	0.0056	0.0052	0.0049	0.0043	0.0039	0.0036
200 km	0.0231	0.0200	0.0180	0.0167	0.0084	0.0074	0.0067	0.0062	0.0059	0.0052	0.0047	0.0043
250 km	0.0394	0.0341	0.0306	0.0283	0.0098	0.0085	0.0077	0.0072	0.0069	0.0060	0.0054	0.0050
300 km	0.0592	0.0514	0.0463	0.0430	0.0111	0.0097	0.0088	0.0082	0.0079	0.0069	0.0062	0.0058
€/kWh	1000 MW											
	HVAC				HVDC VSC				HVDC LCC			
Transm. Length	8 m/s	9m/s	10m/s	11m/s	8 m/s	9m/s	10m/s	11m/s	8 m/s	9m/s	10m/s	11m/s
50 km	0.0028	0.0024	0.0022	0.0020	0.0041	0.0036	0.0033	0.0030	0.0030	0.0026	0.0023	0.0022
100 km	0.0055	0.0048	0.0043	0.0040	0.0053	0.0046	0.0042	0.0039	0.0039	0.0034	0.0031	0.0029
150 km	0.0084	0.0073	0.0066	0.0061	0.0065	0.0057	0.0051	0.0048	0.0049	0.0043	0.0038	0.0036
200 km	0.0208	0.0181	0.0163	0.0151	0.0077	0.0067	0.0061	0.0056	0.0059	0.0051	0.0046	0.0043
250 km	0.0362	0.0315	0.0285	0.0264	0.0089	0.0078	0.0070	0.0066	0.0068	0.0059	0.0054	0.0050
300 km	0.0606	0.0527	0.0475	0.0440	0.0101	0.0089	0.0080	0.0075	0.0078	0.0068	0.0061	0.0057

Table 6.8: Lowest energy transmission costs for each transmission technology, windfarm size, average wind speed and transmission distance. Part Two

From Tables 6.7 and 6.8 it can be observed that for the same transmission technology and distance an increase of the wind average speed leads to a decrease of the energy transmission cost. This should be expected since the energy output from the windfarm is higher for higher wind speeds. A first look in the above listed results shows that HVDC LCC systems have generally lower transmission cost than HVAC and HVDC VSC systems. A better illustration of the energy cost transmission comparison is provided by the graphical representation of the results.

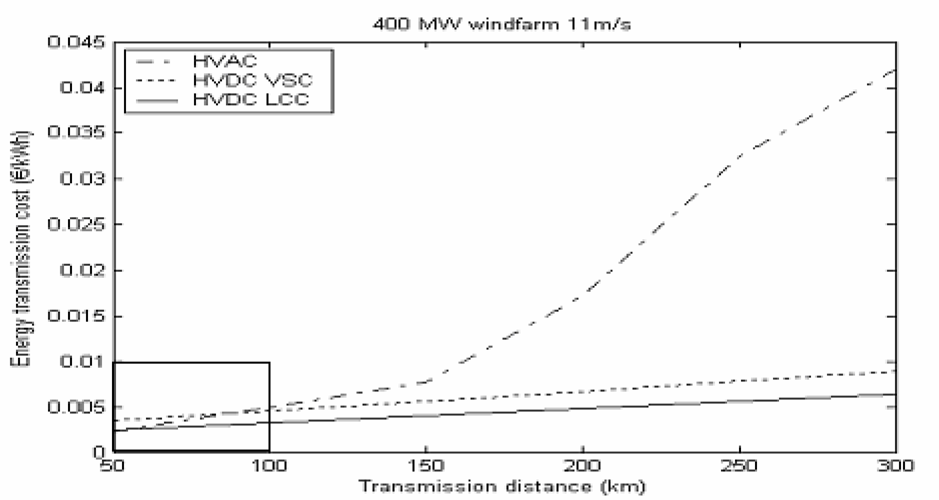

Figure 6.3: Energy transmission cost vs. transmission distance. Windfarm rated at 400 MW, average wind speed of 11 m/s.

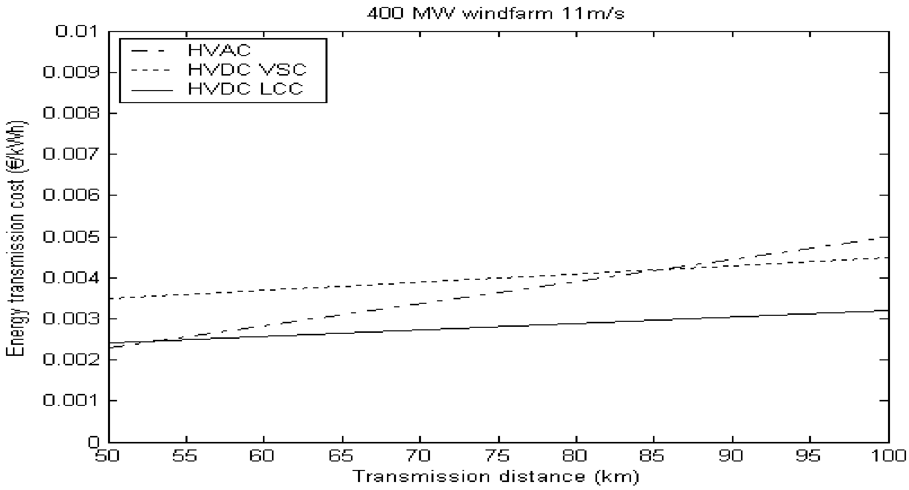

Figure 6.4: Energy transmission cost vs. transmission distance. Windfarm rated at 400 MW, average wind speed of 11 m/s. Detailed area.

Figures 6.3 and 6.4 show that the energy transmission cost for HVDC systems presents a linear dependence to distance, with VSC systems having a higher initial value and gradient compared to LCC systems. Thus the energy transmission cost for VSC systems is always higher to the corresponding value for LCC systems for all transmission distances. The value of the energy transmission cost for HVAC systems appears to have a less uniform behavior, presenting a small increase versus distance for smaller transmission distances and a much higher one when the transmission distance exceeds 150 km. This phenomenon can be explained by observing the results given in Appendix 6.1. While for HVDC systems for a given windfarm, the layout that presents the lowest transmission cost is the same for all distances (number and rating of converter stations and number of cables), for HVAC systems the configuration can change significantly for different transmission distances, not only concerning the number of cables and transformers used (Table 4.1) but also the transmission voltage.

In Figure 6.4 the break even distances between HVAC and HVDC transmission can be distinguished. For the specific windfarm and average wind speed the break even distance between HVAC and HVDC LCC is almost 52 km while between HVAC and HVDC VSC around 85 km. Even though the values of the energy transmission cost and break even distances vary, the same form of plots appear in all cases of windfarms and wind average speeds. In Figure 6.5 the energy transmission cost for a 600 MW windfarm (average speed of 11m/s) is shown while in Figures 6.6 the case of a 900 MW (11m/s average wind speed) windfarm is presented.

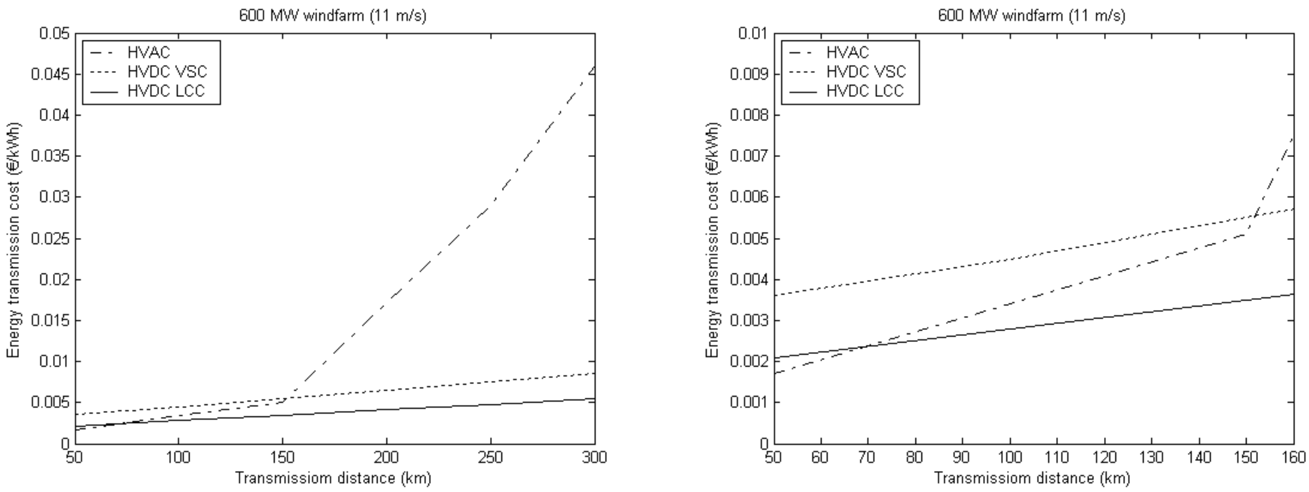

Figure 6.5: Energy transmission cost vs. transmission distance. Windfarm rated at 600 MW, average wind speed of 11 m/s.

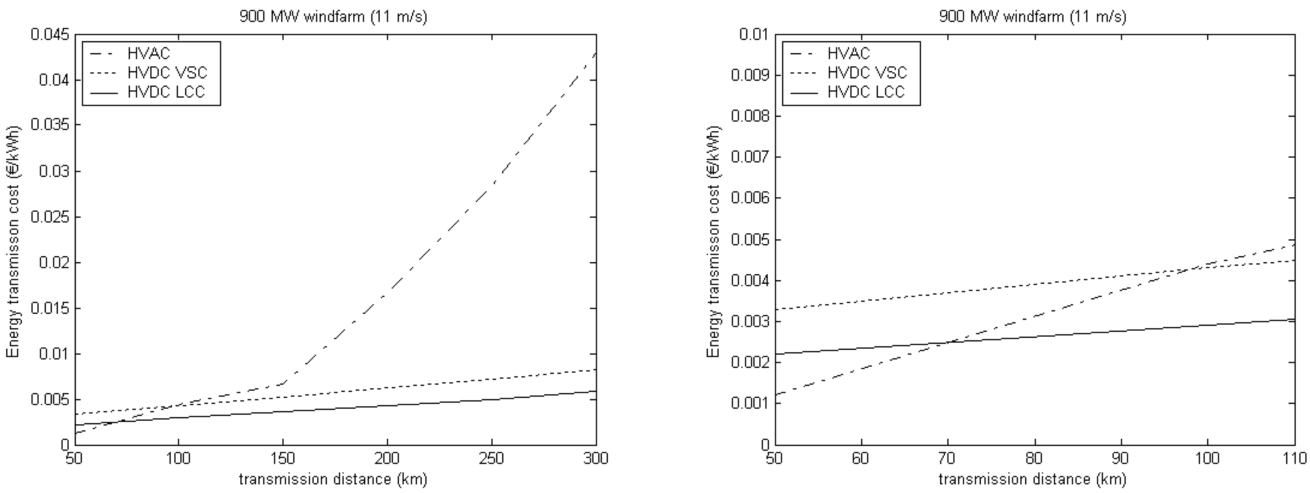

Figure 6.6: Energy transmission cost vs. transmission distance. Windfarm rated at 900 MW, average wind speed of 11 m/s.

The graphs for all windfarm's rated powers and average wind speeds are given in Appendix 6.2.

According to the results of the energy transmission cost for the three transmission technologies the one that presents the lowest cost almost in all transmission distances is the HVDC LCC technology. However there are two major parameters that where not taken in account in the model for the energy transmission cost. The first parameter is the cost of the offshore platforms. As it was mentioned in Chapter 2, all three solutions require offshore construction to host the necessary equipment. The largest and thus the most costly constructions would be required in HVDC LCC systems since its converter stations occupy much larger space. HVDC VSC offshore platforms would be smaller than the ones used in LCC solutions but much larger than the ones used in HVAC systems. Besides the offshore platform in HVDC LCC transmission system, also a diesel generator would be required offshore in order to supply power to the valves at the beginning of transmission as mentioned in Chapter 2. According to that, the energy transmission cost for HVDC LCC systems would have the largest burden, followed by HVDC VSC and finally HVAC systems.

The second and most significant parameter not considered is the cost for upgrading the grid onshore in order to connect the transmission system from the windfarm. Connecting a windfarm of several hundreds MW would have a tremendous impact on the power system's stability. A detailed study is required for every size of windfarm, transmission solution and the possible connection point in order to estimate the cost of the grid upgrade. Because of the special characteristics of HVDC VSC systems (independent control of active and reactive power), the extra cost for the grid upgrade will be significantly lower compared to HVDC LCC and HVAC transmission systems. So if the cost of upgrading the grid is included HVDC VSC solutions could finally appear to have smaller energy transmission cost compared to the other two technologies in contradiction to the results listed in Tables 6.7 and 6.8.

6.3.2 Modified Energy Transmission Cost Model and Results

As mentioned above, some cost parameters were not included in the energy transmission cost model. The addition of these costs would mostly aggravate the energy transmission cost for the HVDC LCC transmission systems. In order to determine the percentage for which the total investment cost of HVDC LCC systems can be increased and still provide a better economically solution than HVDC VSC systems, the model of Section 6.3 was used again. In this case, the investment cost for HVDC LCC was gradually increased. In all studied cases, only after increasing the investment cost of HVDC LCC systems above 35-40% of the initial, did HVDC VSC provide a lower energy transmission cost. It has to be noticed that naturally the initial cost also for HVDC VSC systems should be increased in order to include the investment for the offshore platforms. Nonetheless the above mentioned percentage provides a sense of the difference of the investment costs between the two technologies.

In the model of Section 6.3 the interest rate *r* was set to 3%. Having a low interest rate makes the contribution of the investment cost to the energy transmission less important while the influence of the losses and the energy unavailability is increased. It is thus important to investigate the case of having a much higher interest and to observe the effect that this change has in the energy transmission cost of the several transmission systems. For this reason the interest rate is now set to 10%. In Figures 6.7 and 6.8 the energy transmission cost comparison for a 500 MW windfarm (wind speed 11m/sec) and an interest rate of 10% is presented.

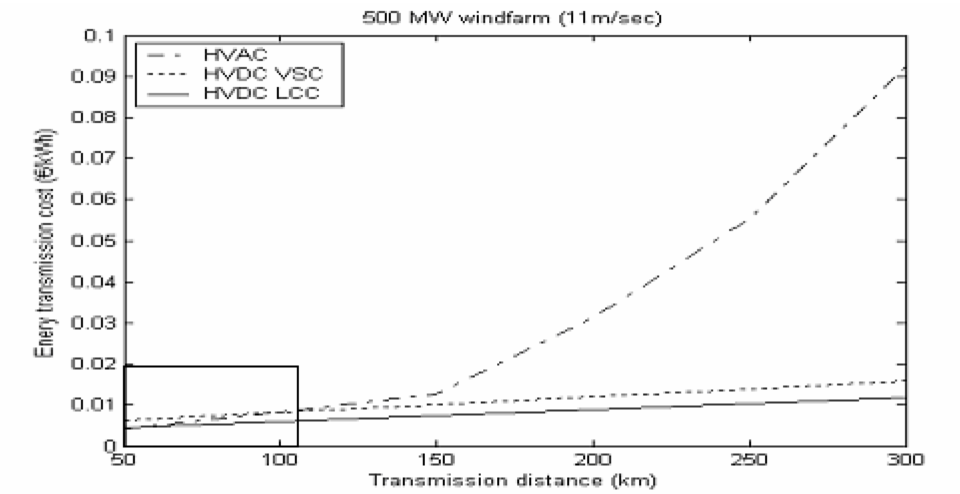

Figure 6.7: Energy transmission cost vs. transmission distance. Windfarm rated at 500 MW, average wind speed of 11 m/s, interest rate at 10%

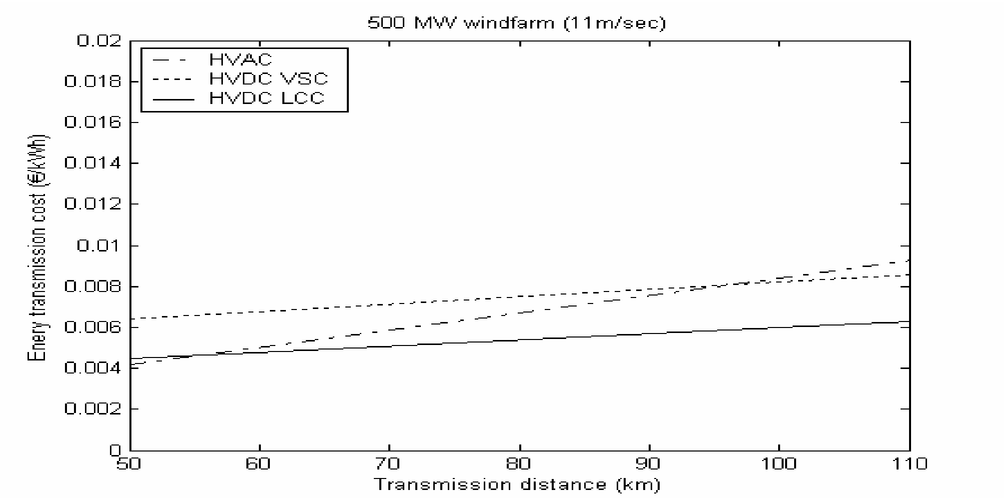

Figure 6.8: Energy transmission cost vs. transmission distance. Windfarm rated at 500 MW, average wind speed of 11 m/s, interest rate at 10%. Area of detail

As it was expected the energy transmission cost for all three transmission technologies has increased (see Appendix E for comparison). Nevertheless HVDC LCC continues to have a lower energy transmission cost compared to HVDC VSC for all transmission distances. This result is logical since generally HVDC VSC does not only present higher losses and energy unavailability but also higher investment cost compared to HVDC LCC. Thus, increasing the interest rate results in even greater difference in the energy transmission cost between the two technologies. The same trend appears in the cases of 700 MW and 1000 MW presented in Figures 6.9 and 6.10. The tables containing the energy transmission cost results for all windfarm's rated powers and 10% interest rate are given in Appendix F.

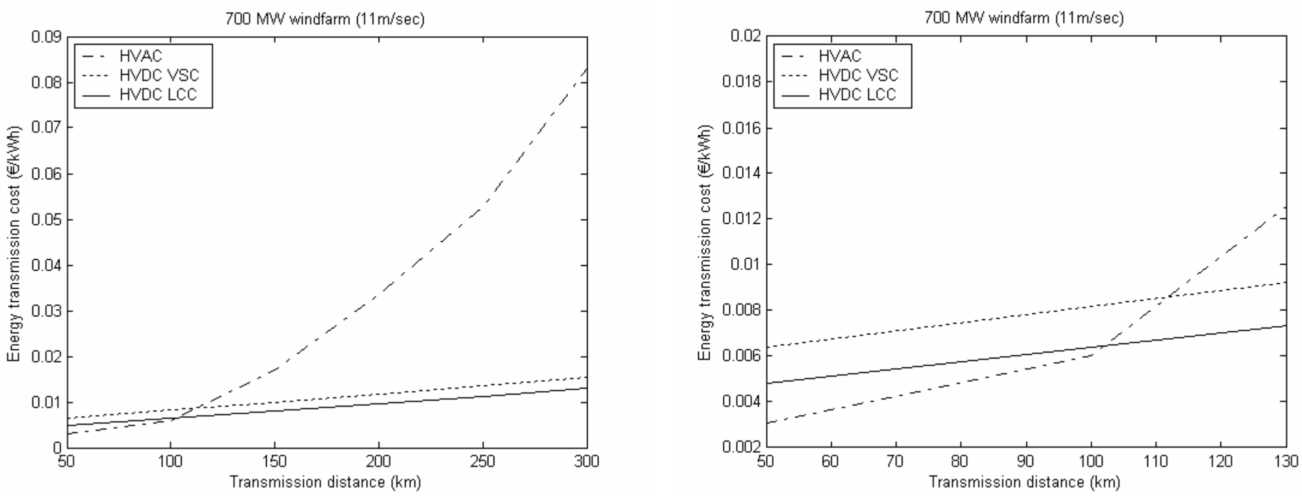

Figure 6.9: Energy transmission cost vs. transmission distance. Windfarm rated at 700 MW, average wind speed of 11 m/s, interest rate at 10%

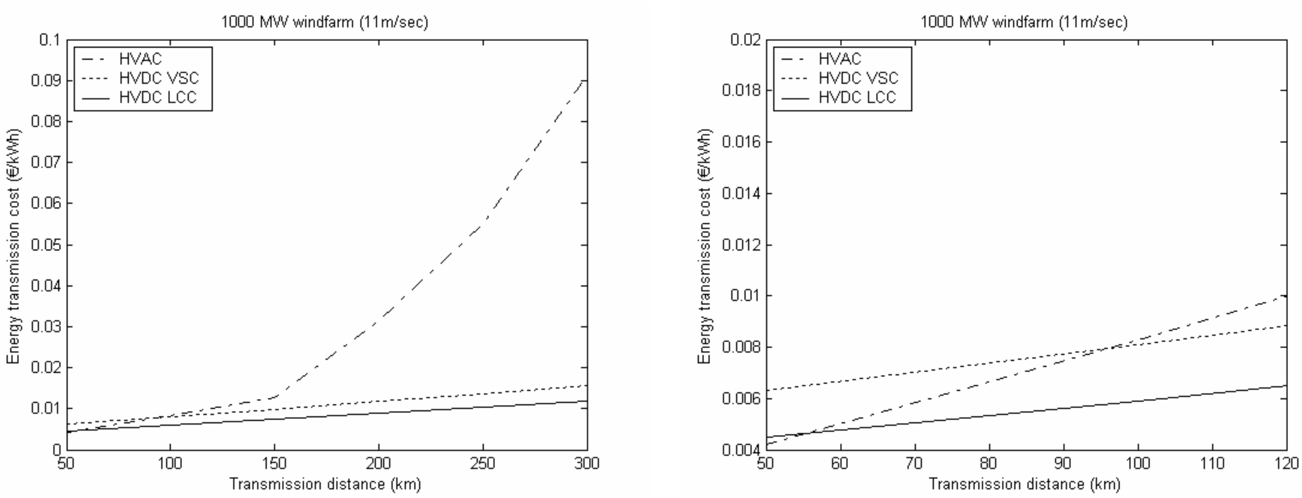

Figure 6.10: Energy transmission cost vs. transmission distance. Windfarm rated at 1000 MW, average wind speed of 11 m/s, interest rate at 10%

6.4 Conclusions

In order to evaluate the energy transmission cost for all transmission technologies and all sizes of windfarms, a model was developed having the losses, the energy unavailability and the investment cost as major inputs. The comparison of the results showed that HVDC LCC systems have lower transmission cost compared to HVDC VSC for all transmission distances. Changing the interest rate does not change this behaviour. HVDC VSC systems can be more profitable than HVDC LCC if the cost of the onshore grid upgrade, the offshore platforms and other auxiliary equipment needed in HVDC LCC, increases the investment cost of HVDC LCC significantly. The energy transmission cost for HVAC systems presents a low value for short transmission distances, even lower than HVDC LCC for very short distances, but has the tendency to increase rapidly above the distance of 100 km.

6.5 References

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7

Comparison of Different HVAC-HVDC Combinations

7.1 Introduction

In this chapter transmission systems that combine all three transmission technologies shall be examined. The configurations of these transmission systems were chosen by Barberis [7.1] and Todorovic [7.2] in order to examine the behavior of the losses in combined transmission and not in order to provide the best economical solutions for real case projects. Thus, most of the configurations are overrated, increasing the initial investment cost and consequently the energy transmission cost. The small number of different configurations analyzed provides a limited set of results, from which specific conclusions can be drawn regarding the energy transmission cost. Nevertheless, the same approach, as for the individual HVAC-HVDC systems, is followed in order to evaluate the energy availability and the energy transmission cost.

7.2 Presentation of Selected Configurations and Calculation of the Energy Transmission Cost

For the combined HVAC-HVDC transmission systems only 500 MW and 1000 MW windfarm were considered. The choices for the transmission distance was limited to 50, 100 and 200 km. The three following, general combinations were compared:

- HVAC + HVDC VSC
- HVAC + HVDC LCC
- HVDC LCC + HVDC VSC

The specific configurations for each solution, based on the transmission distance and the size of the windfarm, are presented in Tables 7.1 and 7.2.

500 MW windfarm, 50 km transmission distance						
	HVAC + HVDC VSC		HVAC + HVDC LCC		HVDC LCC + HVDC VSC	
	Case 1	Case 2	Case 1	Case 2	Case 1	Case 2
Rated power	280 MW (400kV) AC+ 220 MW VSC	150 MW (220kV) AC+ 350 MW VSC	200 MW (220kV) AC + 300 MW LCC	60 MW (220kV) AC+ 440 MW LCC	300 MW LCC+ 220 MW VSC	250 MW LCC+ 350 VSC
Cable numbers	1 (AC) + 2 (VSC)	1 (AC) + 2 (VSC)	1 (AC) + 1(LCC)	1 (AC) + 1(LCC)	1 (LCC) + 2 (VSC)	1 (LCC) + 2 (VSC)
500 MW windfarm, 100 km transmission distance						
	HVAC + HVDC VSC		HVAC + HVDC LCC		HVDC LCC + HVDC VSC	
	Case 1	Case 2	Case 1	Case 2	Case 1	Case 2
Rated power	280 MW (400kV) AC+ 220 MW VSC	150 MW (220kV) AC+ 350 MW VSC	370 MW (400kV) AC + 130 MW LCC	250 MW (400kV) AC+ 250 MW LCC	300 MW LCC+ 220 MW VSC	250 MW LCC+ 350 VSC
Cable numbers	1 (AC) + 2 (VSC)	1 (AC) + 2 (VSC)	1 (AC) + 1(LCC)	1 (AC) + 1(LCC)	1 (LCC) + 2 (VSC)	1 (LCC) + 2 (VSC)
500 MW windfarm, 200 km transmission distance						
	HVAC + HVDC VSC		HVAC + HVDC LCC		HVDC LCC + HVDC VSC	
	Case 1	Case 2	Case 1	Case 2	Case 1	Case 2
Rated power	280 MW (220kV) AC+ 220 MW VSC	150 MW (220kV) AC+ 350 MW VSC	370 MW (400kV) AC + 130 MW LCC	250 MW (400kV) AC+ 250 MW LCC	300 MW LCC+ 220 MW VSC	250 MW LCC+ 350 VSC
Cable numbers	1 (AC) + 2 (VSC)	1 (AC) + 2 (VSC)	2 (AC) + 1(LCC)	1 (AC) + 1(LCC)	1 (LCC) + 2 (VSC)	1 (LCC) + 2 (VSC)

Table 7.1: Configurations for the study of combined transmission systems. Windfarm rated at 500 MW

1000 MW windfarm, 50 km transmission distance					
	HVAC + HVDC VSC	**HVAC + HVDC LCC**		**HVDC LCC + HVDC VSC**	
		Case 1	Case 2	Case 1	Case 2
Rated power	200 MW (220kV) AC+ (2x350+220) MW VSC	200 MW (400kV) AC + (600+250) MW LCC	330 MW (400kV) AC+ (600+130) MW LCC	600 MW LCC+ (350+220) MW VSC	250 MW LCC+ (2x350+220) VSC
Cable numbers	1 (AC) + 4 (VSC)	1 (AC) + 2(LCC)	1 (AC) + 2(LCC)	1 (LCC) + 24(VSC)	1 (LCC) + 6 (VSC)
1000 MW windfarm, 100 km transmission distance					
	HVAC + HVDC VSC	**HVAC + HVDC LCC**		**HVDC LCC + HVDC VSC**	
		Case 1	Case 2	Case 1	Case 2
Rated power	500 MW (400kV) AC+ (350+220) MW VSC	800 MW (400kV) AC + 250 MW LCC	900 MW (400kV) AC+ 130 MW LCC	600 MW LCC+ (350+220) MW VSC	250 MW LCC+ (2x350+220) VSC
Cable numbers	1 (AC) + 4 (VSC)	2 (AC) + 1(LCC)	2 (AC) + 1(LCC)	1 (LCC) + 4(VSC)	1 (LCC) + 6 (VSC)
1000 MW windfarm, 200 km transmission distance					
	HVAC + HVDC VSC	**HVAC + HVDC LCC**		**HVDC LCC + HVDC VSC**	
		Case 1	Case 2	Case 1	Case 2
Rated power	500 MW (220kV) AC+ (350+220) MW VSC	800 MW (220kV) AC + 250 MW LCC	900 MW (220kV) AC+ 130 MW LCC	600 MW LCC+ (350+220) MW VSC	250 MW LCC+ (2x350+220) VSC
Cable numbers	2 (AC) + 24(VSC)	3 (AC) + 1(LCC)	4 (AC) + 1(LCC)	1 (LCC) + 4(VSC)	1 (LCC) + 6 (VSC)

Table 7.2: Configurations for the study of combined transmission systems. Windfarm rated at 1000 MW

The energy availability of each configuration is calculated according to the algorithm presented in Chapter 5. The evaluation of the losses has been made by Barberis [7.1] and Todorovic [7.2]. The results concerning the losses and the energy unavailability are listed in Tables 7.3 and 7.4.

500 MW windfarm, 50 km transmission distance												
	HVAC + HVDC VSC				**HVAC + HVDC LCC**				**HVDC LCC + HVDC VSC**			
	Case 1		Case 2		Case 1		Case 2		Case 1		Case 2	
Wind Average speed (m/s)	Losses (%)	Energy Un(%)	Losses (%)	Energy Un(%)	Losses (%)	Energy Un(%)	Losses (%)	Energy Un(%)	Losses (%)	Energy Un(%)	Losses (%)	Energy Un(%)
8	2.00	2.99	3.09	4.89	1.54	1.14	1.73	1.32	2.65	2.70	2.91	3.10
9	2.02	3.28	3.11	5.20	1.54	1.25	1.70	1.38	2.61	2.98	2.86	3.40
10	2.03	3.51	3.13	5.43	1.54	1.32	1.68	1.41	2.59	3.20	2.84	3.62
11	2.05	3.67	3.14	5.59	1.54	1.38	1.67	1.44	2.58	3.35	2.83	3.79
500 MW windfarm, 100 km transmission distance												
	HVAC + HVDC VSC				**HVAC + HVDC LCC**				**HVDC LCC + HVDC VSC**			
	Case 1		Case 2		Case 1		Case 2		Case 1		Case 2	
Wind Average speed (m/s)	Losses (%)	Energy Un(%)	Losses (%)	Energy Un(%)	Losses (%)	Energy Un(%)	Losses (%)	Energy Un(%)	Losses (%)	Energy Un(%)	Losses (%)	Energy Un(%)
8	3.32	3.21	3.94	5.18	2.70	1.31	2.69	1.19	2.92	2.91	3.25	3.30
9	3.21	3.53	3.94	5.51	2.57	1.41	2.55	1.30	2.89	3.20	3.22	3.62
10	3.15	3.76	3.94	5.75	2.49	1.47	2.46	1.39	2.88	3.43	3.20	3.85
11	3.11	3.94	3.94	5.92	2.44	1.52	2.40	1.45	2.87	3.60	3.20	4.03
500 MW windfarm, 200 km transmission distance												
	HVAC + HVDC VSC				**HVAC + HVDC LCC**				**HVDC LCC + HVDC VSC**			
	Case 1		Case 2		Case 1		Case 2		Case 1		Case 2	
Wind Average speed (m/s)	Losses (%)	Energy Un(%)	Losses (%)	Energy Un(%)	Losses (%)	Energy Un(%)	Losses (%)	Energy Un(%)	Losses (%)	Energy Un(%)	Losses (%)	Energy Un(%)
8	7.04	3.80	6.97	5.77	7.12	5.77	6.75	0.95	3.46	3.32	3.93	3.70
9	6.88	4.16	6.98	6.14	6.89	6.15	6.55	1.03	3.46	3.66	3.93	4.05
10	6.78	4.43	7.00	6.41	6.75	6.41	6.42	1.09	3.46	3.92	3.93	4.32
11	6.72	4.64	7.02	6.61	6.65	6.61	6.34	1.13	3.46	4.10	3.93	4.52

Table 7.3: Average losses and energy unavailability of combined transmission systems. Windfarm rated at 500 MW

As someone would expect, according to the energy unavailability results of Chapter 5, the transmission systems that present the lowest energy unavailability are the ones that are combinations of HVAC and HVDC LCC technologies. Also the combinations of HVDC VSC with the other two technologies appear to have lower values of unavailability compared to the single HVDC VSC systems studied in Chapter 5. That can be explained by the fact that all of the transmission systems presented in Tables 7.1 and 7.2 consist of multiple parallel poles with total transmission capacity well above the value of the rated power of the windfarm. The same observations can be made for the transmission systems from the 1000 MW windfarm presented in Table 7.4.

1000 MW windfarm, 50 km transmission distance										
	HVAC + HVDC VSC		**HVAC + HVDC LCC**				**HVDC LCC + HVDC VSC**			
			Case 1		Case 2		Case 1		Case 2	
Wind Average speed (m/s)	Losses (%)	Energy Un(%)	Losses (%)	Energy Un(%)	Losses (%)	Energy Un(%)	Losses (%)	Energy Un(%)	Losses (%)	Energy Un(%)
8	3.16	2.76	1.47	0.85	1.34	0.92	2.42	1.46	3.14	2.04
9	3.20	3.15	1.44	0.95	1.31	1.01	2.46	1.67	3.18	2.35
10	3.22	3.44	1.43	1.01	1.30	1.08	2.49	1.83	3.20	2.59
11	3.24	3.67	1.42	1.07	1.30	1.14	2.52	1.95	3.23	2.77

1000 MW windfarm, 100 km transmission distance										
	HVAC + HVDC VSC		**HVAC + HVDC LCC**				**HVDC LCC + HVDC VSC**			
			Case 1		Case 2		Case 1		Case 2	
Wind Average speed (m/s)	Losses (%)	Energy Un(%)	Losses (%)	Energy Un(%)	Losses (%)	Energy Un(%)	Losses (%)	Energy Un(%)	Losses (%)	Energy Un(%)
8	3.01	2.59	2.58	0.49	2.37	0.54	2.64	1.59	3.54	2.18
9	3.02	2.94	2.56	0.56	2.32	0.61	2.70	1.82	3.58	2.51
10	3.03	3.20	2.55	0.61	2.44	0.66	2.74	1.99	3.61	2.76
11	3.04	3.39	2.55	0.65	2.40	0.70	2.77	2.12	3.63	2.95

1000 MW windfarm, 200 km transmission distance										
	HVAC + HVDC VSC		**HVAC + HVDC LCC**				**HVDC LCC + HVDC VSC**			
			Case 1		Case 2		Case 1		Case 2	
Wind Average speed (m/s)	Losses (%)	Energy Un(%)	Losses (%)	Energy Un(%)	Losses (%)	Energy Un(%)	Losses (%)	Energy Un(%)	Losses (%)	Energy Un(%)
8	6.79	2.15	6.79	1.08	7.29	0.77	3.08	1.86	3.93	2.46
9	6.66	2.45	6.68	1.24	7.18	0.86	3.16	2.11	3.93	2.83
10	6.58	2.69	6.61	1.36	7.11	0.94	3.22	2.31	3.93	3.11
11	6.52	2.86	6.56	1.45	7.06	0.99	3.26	2.46	3.93	3.32

Table 7.4: Average losses and energy unavailability of combined transmission systems. Windfarm rated at 1000 MW

Applying the components cost models of Chapter 6 the energy transmission cost can be evaluated. It is important to notice that for the HVAC lines that are included in the configurations listed in Tables 7.1 and 7.2 the transformers are assumed to have the exact rated power given. For example, in case 2 of HVAC-HVDC LCC transmission system from a 500 MW windfarm with 50 km transmission distance, both the offshore and onshore transformers are assumed to be of 60 MW rated power. This power is used in order to estimate the cost of the transformers according to Equation 6.4, while the losses are assumed not to change. The results concerning the energy transmission cost are listed in Tables 7.5 and 7.6.

Transmission Cost (€/kWh)	**500 MW windfarm, 50 km transmission distance**					
	HVAC + HVDC VSC		**HVAC + HVDC LCC**		**HVDC LCC + HVDC VSC**	
Wind Speed	Case 1	Case 2	Case 1	Case 2	Case 1	Case 2
8 m/s	0.0048	0.0054	0.0042	0.0050	0.0039	0.0045
9 m/s	0.0042	0.0047	0.0037	0.0043	0.0034	0.0040
10 m/s	0.0038	0.0043	0.0033	0.0039	0.0030	0.0036
11 m/s	0.0035	0.0040	0.0031	0.0036	0.0028	0.0033
Transmission Cost (€/kWh)	**500 MW windfarm, 100 km transmission distance**					
	HVAC + HVDC VSC		**HVAC + HVDC LCC**		**HVDC LCC + HVDC VSC**	
Wind Speed	Case 1	Case 2	Case 1	Case 2	Case 1	Case 2
8 m/s	0.0083	0.0088	0.0069	0.0077	0.0052	0.0060
9 m/s	0.0072	0.0077	0.0060	0.0067	0.0045	0.0052
10 m/s	0.0065	0.0069	0.0054	0.0060	0.0041	0.0047
11 m/s	0.0060	0.0064	0.0050	0.0056	0.0038	0.0044
Transmission Cost (€/kWh)	**500 MW windfarm, 200 km transmission distance**					
	HVAC + HVDC VSC		**HVAC + HVDC LCC**		**HVDC LCC + HVDC VSC**	
Wind Speed	Case 1	Case 2	Case 1	Case 2	Case 1	Case 2
8 m/s	0.0141	0.0151	0.0215	0.0124	0.0079	0.0090
9 m/s	0.0123	0.0132	0.0187	0.0107	0.0069	0.0079
10 m/s	0.0111	0.0119	0.0168	0.0097	0.0062	0.0071
11 m/s	0.0103	0.0110	0.0155	0.0089	0.0058	0.0066

Table 7.5: Energy transmission cost of combined transmission systems. Windfarm rated at 500 MW.

Transmission Cost (€/kWh)	1000 MW windfarm, 50 km transmission distance				
	HVAC + HVDC VSC	HVAC + HVDC LCC		HVDC LCC + HVDC VSC	
Wind Speed		Case 1	Case 2	Case 1	Case 2
8 m/s	0.0051	0.0039	0.0036	0.0042	0.0046
9 m/s	0.0044	0.0034	0.0031	0.0036	0.0041
10 m/s	0.0040	0.0031	0.0028	0.0033	0.0037
11 m/s	0.0037	0.0029	0.0026	0.0030	0.0034
Transmission Cost (€/kWh)	**1000 MW windfarm, 100 km transmission distance**				
	HVAC + HVDC VSC	**HVAC + HVDC LCC**		**HVDC LCC + HVDC VSC**	
Wind Speed		Case 1	Case 2	Case 1	Case 2
8 m/s	0.0060	0.0066	0.0061	0.0055	0.0061
9 m/s	0.0052	0.0057	0.0053	0.0048	0.0054
10 m/s	0.0047	0.0051	0.0048	0.0043	0.0048
11 m/s	0.0044	0.0048	0.0045	0.0040	0.0045
Transmission Cost (€/kWh)	**1000 MW windfarm, 200 km transmission distance**				
	HVAC + HVDC VSC	**HVAC + HVDC LCC**		**HVDC LCC + HVDC VSC**	
Wind Speed		Case 1	Case 2	Case 1	Case 2
8 m/s	0.0146	0.0162	0.0204	0.0081	0.0092
9 m/s	0.0127	0.0141	0.0177	0.0071	0.0080
10 m/s	0.0115	0.0127	0.0160	0.0064	0.0072
11 m/s	0.0106	0.0118	0.0148	0.0059	0.0067

Table 7.6: Energy transmission cost of combined transmission systems. Windfarm rated at 1000 MW.

It is possible to notice from the results of Table 7.5 and 7.6 that the energy transmission cost, of the transmission systems that consist of combinations of transmission technologies, is relatively higher than the ones that were presented in Table 6.7. There are some cases though that the energy transmission cost can be considered reasonable, always in relation to the transmission cost of the single technology transmission systems. For example, in Table 7.5 cases 1 and 2 for the LCC-VSC transmission solution present a transmission cost of 0.0028 and 0.0033 €/kWh respectively (for average wind speed of 11m/s). There are two major drawbacks though for these solutions. By observing the configurations of these solutions (Table 7.1) one can see that three offshore converters are utilised. The offshore platforms required to host these converters, as explained before, are complex, big and thus very costly. Including the cost for the construction of the offshore platforms would raise the value of the energy transmission significantly. The second drawback, that applies for all combined transmission systems, is the fact that their maintenance would have a much larger cost. A transmission system that combines two or more transmission technologies would aggravate logistics, requiring multiple personnel's specialization and spare parts for all transmission technologies.

7.3 1000 MW Windfarm with Multiple Connection Points to Shore

Besides the combinations of the transmission technologies presented above, three cases of transmission solutions from a 1000 MW windfarm are analysed. In these cases the windfarm is connected to three different onshore grids, utilizing all three transmission technologies studied so far. An illustration of one of these cases is presented in Figure 7.1.

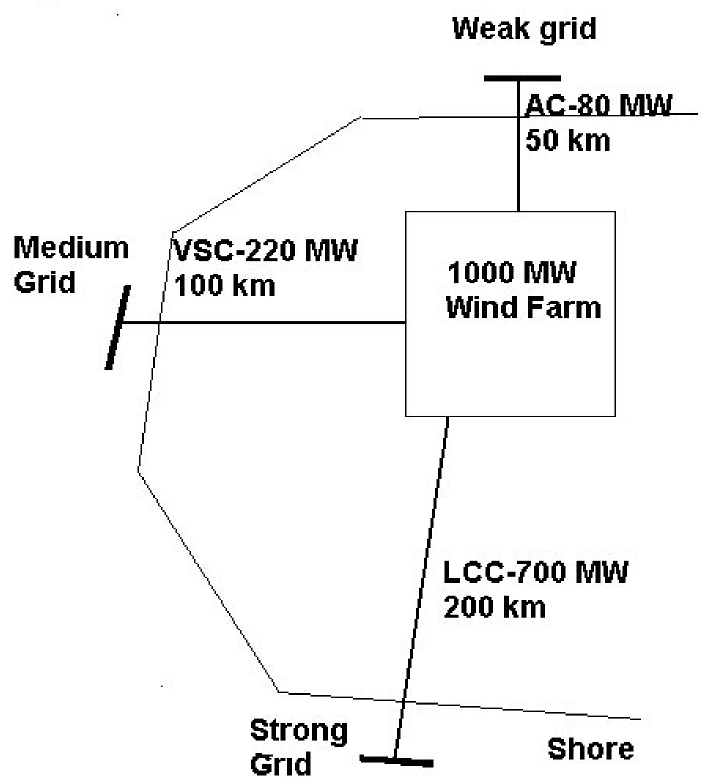


Figure 7.1: 1000 MW windfarm at different distances to shore (source [7.1], [7.2])

The three different configurations for this solution are the following:

- Case 1: 80 MW AC + 220 MW VSC + (600+130) MW LCC (Figure 7.1)
- Case 2: 50 MW AC + 350 MW VSC + (440+250) MW LCC
- Case 3: 180 MW AC + 220 MW VSC + (440+250) MW LCC

Only the rated power of each transmission technology changes every time while the distance to shore and the condition of the onshore grid remain the same.

- The HVAC system has a voltage level of 220 kV and it connected to a weak grid 50 km from the offshore substation.
- The HVDC VSC system is connected to a grid of medium strength at a distance of 100 km from the offshore substation.
- The HVDC LCC system is connected to a strong grid 200 km from the offshore substation.

The average losses for the cases described above were calculated by Barberis [7.1] and Todorovic [7.2]. The losses and the results concerning the energy unavailability and the energy transmission cost are presented in Table 7.7.

1000 MW	**Case 1**			**Case 2**			**Case 3**		
Wind Speed	Losses (%)	Energy Unav. (%)	Energy Tr. Cost (€/kWh)	Losses (%)	Energy Unav. (%)	Energy Tr. Cost (€/kWh)	Losses (%)	Energy Unav. (%)	Energy Tr. Cost (€/kWh)
8 m/s	2.57	2.5849	0.0070	2.64	2.0578	0.0071	2.28	1.9917	0.0071
9 m/s	2.60	2.6240	0.0061	2.71	2.1918	0.0062	2.31	2.1380	0.0062
10 m/s	2.63	2.7222	0.0055	2.76	2.2991	0.0056	2.33	2.2431	0.0056
11 m/s	2.65	2.7926	0.0051	2.80	2.3725	0.0052	2.34	2.3194	0.0056

Table 7.7: Average power losses, energy unavailability and energy transmission cost for transmission solutions from a 1000 MW windfarm with multiple connection points to shore.

7.4 Conclusions

As in the dual transmission systems of section 7.2, the energy transmission cost for the solutions presented in Section 7.3 have relatively higher value compared to the configurations that consist of a single technology transmission system. As mentioned before, besides the parameters that were taken in account for the evaluation of energy transmission cost (cost of components, reliability of components etc), other parameters can have a major effect in the economical performance of a transmission system. The more complex is a system to be constructed and maintained the more is the value of the energy transmission cost expected to rise. Systems like the ones described in Sections 7.2 and 7.3 are neither simple to construct nor to maintain. If nevertheless, the technical requirements of a potential windfarm project determine the need for such a combination to be chosen, a more thorough study concerning the possible solutions should be made. For example, choosing transmission systems that have rated power much closer to the required one might as well improve the overall economical performance. It is very likely that the above calculated energy transmission costs could be reduced in case of a more careful choice of transmission system's characteristics.

7.5 References

[7.1] Barberis Negra N., "Evaluation of Losses of HVDC Solutions for Large Offshore Wind Farms", Master's thesis, Royal Institute of Technology, Department of Electrical Engineering, Stockholm, Sweden, 2005.

[7.2] Todorovic J., "Losses Evaluation of HVAC Connections of Large Offshore Wind Farms", Master's thesis, Royal Institute of Technology, Department of Electrical Engineering, Stockholm, Sweden, 2004.

8

Summary

As the technology surrounding wind power systems becomes more advanced, projects for windfarms in the size range of several hundreds MW are being proposed. These larger windfarms are mainly considered to be located offshore where a significant wind potential exists and in such distances that they cannot be observed from shore. The long transmission distance to shore makes the design and selection of the transmission system a key element to the overall performance of the wind power system.

A well designed transmission system should transmit as much as possible of the produced energy at the lowest possible cost. The purpose of this study was to investigate several transmission solutions from large offshore windfarms and perform an economic comparison. The major parameters that influence the economic performance of a transmission system are its efficiency and the total installation cost. Generally, the efficiency describes the quality of a system to perform for the purpose that it was designed for. In the case of a transmission system the efficiency describes the ability to transmit the produced by the windfarm energy. Losses and failure in the transmission system decrease its efficiency, namely decrease the amount of produced energy that can reach the market. The three aforementioned elements (losses, reliability, investment cost) were the basic parameters around which the final economic model was built in order to perform the analysis. Many assumptions had to be made in order for this study to be concluded. Even though all of them are mentioned in the main body of this report, a summary of the assumptions made is given in Appendix G.

As it was mentioned before the in this report transmission solutions from large offshore windfarms were compared economically. Three were the transmission technologies investigated: HVAC, HVDC LCC and HVDC VSC. The windfarm's size varied from 400 to 1000 MW and the transmission distance from 50 to 300 km. For the offshore location the wind average speed was assumed to be 8, 9, 10 and 11 m/sec.

In order for the power input to the transmission system to be defined, the aggregated power model for the windfarm was used. This model was based on the power curve of a 5 MW single wind turbine and the assumption that the wind speed follows the Rayleigh distribution. All the configurations for the three transmission technologies, the sizes of the windfarm and the transmission distances were made by Barberis [7.1] and Todorovic [7.2] who also provided the average losses.

The next step was to evaluate the energy unavailability of each transmission system, namely the percentage of energy produced by the windfarm but not transmitted due to forced outages. For this purpose, statistical data concerning the failures in the components of each transmission technology were collected and analyzed. The energy availability of each configuration was then calculated based on an algorithm that took in account the aggregated windfarm model and the probability distribution of the wind speed. The results of this study led to some interesting conclusions concerning the energy availability and the methods that could be used in order to improve it. More specifically, systems that constituted of parallel poles or transmission lines had higher energy availability compared to single pole systems. Overrating systems with parallel poles would even more improve the energy availability. Another interesting conclusion drawn was the fact that HVDC VSC transmission systems presented much higher energy unavailability compared to HVDC LCC systems with the same configuration (number of parallel poles, power rating).

The last parameter in the final economic model was the investment cost. A research was carried out in order to determine the cost of each component of each transmission technology. Knowing the cost of the component and the configuration of each transmission system allowed the determination of the investment cost for each case and thus the energy transmission cost. The comparison of the results showed that HVDC LCC transmission systems always presented a lower transmission cost than HVDC VSC systems. The investment cost for HVDC LCC would have to be increased significantly (possible grid upgrade cost, higher cost for offshore platforms) in order for HVDC VSC to provide the lowest transmission cost between the two solutions. HVAC systems can provide very good solutions for short transmission distances. Bellow 100 km of transmission distance their energy transmission, in most of the cases, is lower than the one of HVDC VSC and for shorter distances even lower than HVDC LCC. But for transmission distances above 100 km HVAC systems are the least profitable solution as their energy transmission cost increases rapidly in this interval.

Appendix A

Unavailability and Non-Transmitted Energy due to Forced Outages for HVDC LCC Transmission Systems

Windfarm rated at 400 MW

Monopolar 440 MW								
Transmission Distance	8 m/s		9 m/s		10 m/s		11 m/s	
	%	GWh	%	GWh	%	GWh	%	GWh
50 km	1.5370	25.0455	1.5370	29.5861	1.5370	32.8441	1.5370	35.4745
100 km	1.7601	28.6809	1.7601	33.8806	1.7601	37.6115	1.7601	40.6237
150 km	1.9832	32.3164	1.9832	38.1752	1.9832	42.3789	1.9832	45.7729
200 km	2.2063	35.9518	2.2063	42.4697	2.2063	47.1463	2.2063	50.9221
250 km	2.4294	39.5872	2.4294	46.7642	2.4294	51.9137	2.4294	56.0713
300 km	2.6525	43.2226	2.6525	51.0587	2.6525	56.6811	2.6525	61.2206

Monopolar 500 MW								
Transmission Distance	8 m/s		9 m/s		10 m/s		11 m/s	
	%	GWh	%	GWh	%	GWh	%	GWh
50 km	1.5370	25.0455	1.5370	29.5861	1.5370	32.8441	1.5370	35.4745
100 km	1.7601	28.6809	1.7601	33.8806	1.7601	37.6115	1.7601	40.6237
150 km	1.9832	32.3164	1.9832	38.1752	1.9832	42.3789	1.9832	45.7729
200 km	2.2063	35.9518	2.2063	42.4697	2.2063	47.1463	2.2063	50.9221
250 km	2.4294	39.5872	2.4294	46.7642	2.4294	51.9137	2.4294	56.0713
300 km	2.6525	43.2226	2.6525	51.0587	2.6525	56.6811	2.6525	61.2206

2x Monopolar 250 MW								
Transmission Distance	8 m/s		9 m/s		10 m/s		11 m/s	
	%	GWh	%	GWh	%	GWh	%	GWh
50 km	0.7794	13.0218	0.8570	16.4973	0.9153	19.5587	0.9592	22.1385
100 km	0.8835	14.7614	0.9734	18.7363	1.0408	22.2397	1.0916	25.1934
150 km	0.9882	16.5103	1.0902	20.9848	1.1667	24.9304	1.2243	28.2580
200 km	1.0934	18.2682	1.2075	23.2428	1.2930	27.6307	1.3575	31.3322
250 km	1.1992	20.0353	1.3253	25.5102	1.4198	30.3405	1.4911	34.4160
300 km	1.3055	21.8116	1.4435	27.7870	1.5471	33.0600	1.6252	37.5095

Windfarm rated at 500 MW

Monopolar 500 MW								
Transmission Distance	8 m/s		9 m/s		10 m/s		11 m/s	
	%	GWh	%	GWh	%	GWh	%	GWh
50 km	1.5370	32.1008	1.5370	36.9841	1.5370	41.0524	1.5370	44.3342
100 km	1.7601	36.7604	1.7601	42.3524	1.7601	47.0112	1.7601	50.7694
150 km	1.9832	41.4199	1.9832	47.7208	1.9832	52.9701	1.9832	57.2047
200 km	2.2063	46.0794	2.2063	53.0891	2.2063	58.9290	2.2063	63.6399
250 km	2.4294	50.7389	2.4294	58.4575	2.4294	64.8879	2.4294	70.0751
300 km	2.6525	55.3985	2.6525	63.8258	2.6525	70.8467	2.6525	76.5104

2xMonopolar 250 MW								
Transmission Distance	8 m/s		9 m/s		10 m/s		11 m/s	
	%	GWh	%	GWh	%	GWh	%	GWh
50 km	1.0762	22.4765	1.1667	28.0732	1.2329	32.9296	1.2819	36.9765
100 km	1.2269	25.6246	1.3316	32.0422	1.4082	37.6128	1.4650	42.2563
150 km	1.3780	28.7797	1.4968	36.0176	1.5838	42.3019	1.6482	47.5414
200 km	1.5294	31.9417	1.6623	39.9995	1.7596	46.9969	1.8316	52.8318
250 km	1.6811	35.1107	1.8281	43.9878	1.9356	51.6978	2.0152	58.1275
300 km	1.8332	38.2866	1.9941	47.9825	2.1118	56.4045	2.1990	63.4285

Monopolar 600 MW								
Transmission Distance	8 m/s		9 m/s		10 m/s		11 m/s	
	%	GWh	%	GWh	%	GWh	%	GWh
50 km	1.5370	32.1008	1.5370	36.9841	1.5370	41.0524	1.5370	44.3342
100 km	1.7601	36.7604	1.7601	42.3524	1.7601	47.0112	1.7601	50.7694
150 km	1.9832	41.4199	1.9832	47.7208	1.9832	52.9701	1.9832	57.2047
200 km	2.2063	46.0794	2.2063	53.0891	2.2063	58.9290	2.2063	63.6399
250 km	2.4294	50.7389	2.4294	58.4575	2.4294	64.8879	2.4294	70.0751
300 km	2.6525	55.3985	2.6525	63.8258	2.6525	70.8467	2.6525	76.5104

Windfarm rated at 600 MW

Monopolar 600 MW								
Transmission Distance	8 m/s		9 m/s		10 m/s		11 m/s	
	%	GWh	%	GWh	%	GWh	%	GWh
50 km	1.5370	38.5298	1.5370	44.3843	1.5370	49.2581	1.5370	53.1886
100 km	1.7601	44.1225	1.7601	50.8268	1.7601	56.4081	1.7601	60.9091
150 km	1.9832	49.7152	1.9832	57.2693	1.9832	63.5581	1.9832	68.6296
200 km	2.2063	55.3079	2.2063	63.7118	2.2063	70.7080	2.2063	76.3501
250 km	2.4294	60.9006	2.4294	70.1543	2.4294	77.8580	2.4294	84.0706
300 km	2.6525	66.4933	2.6525	76.5968	2.6525	85.0079	2.6525	91.7911

Monopolar 440 + 250 MW								
Transmission Distance	8 m/s		9 m/s		10 m/s		11 m/s	
	%	GWh	%	GWh	%	GWh	%	GWh
50 km	0.9326	23.3795	1.0083	29.1168	1.0641	34.1034	1.1057	38.2633
100 km	1.0608	26.5930	1.1484	33.1617	1.2130	38.8734	1.2611	43.6399
150 km	1.1895	29.8175	1.2888	37.2176	1.3621	43.6544	1.4167	49.0272
200 km	1.3185	33.0529	1.4297	41.2846	1.5117	48.4463	1.5727	54.4254
250 km	1.4480	36.2992	1.5709	45.3626	1.6615	53.2492	1.7290	59.8343
300 km	1.5780	39.5565	1.7125	49.4516	1.8117	58.0630	1.8857	65.2541

2xMonopolar 300 MW								
Transmission Distance	8 m/s		9 m/s		10 m/s		11 m/s	
	%	GWh	%	GWh	%	GWh	%	GWh
50 km	1.0743	26.9304	1.1641	33.6163	1.2300	39.4196	1.2789	44.2572
100 km	1.2247	30.7016	1.3287	38.3678	1.4049	45.0245	1.4615	50.5751
150 km	1.3755	34.4811	1.4935	43.1271	1.5800	50.6365	1.6442	56.8994
200 km	1.5266	38.2690	1.6585	47.8942	1.7553	56.2557	1.8272	63.2302
250 km	1.6780	42.0652	1.8239	52.6690	1.9309	61.8819	2.0103	69.5675
300 km	1.8298	45.8699	1.9895	57.4516	2.1067	67.5152	2.1936	75.9112

Windfarm rated at 700 MW

Monopolar 500 + Monopolar 250 MW								
Transmission Distance	8 m/s		9 m/s		10 m/s		11 m/s	
	%	GWh	%	GWh	%	GWh	%	GWh
50 km	1.0345	30.2645	1.1120	37.4666	1.1690	43.7029	1.2111	48.8852
100 km	1.1787	34.4827	1.2684	42.7347	1.3343	49.8830	1.3830	55.8247
150 km	1.3232	38.7115	1.4250	48.0132	1.4998	56.0729	1.5552	62.7736
200 km	1.4681	42.9510	1.5820	53.3021	1.6657	62.2729	1.7276	69.7321
250 km	1.6134	47.2010	1.7393	58.6012	1.8318	68.4827	1.9002	76.7001
300 km	1.7590	51.4617	1.8969	63.9108	1.9981	74.7025	2.0731	83.6775

Monopolar 440 + 300 MW								
Transmission Distance	8 m/s		9 m/s		10 m/s		11 m/s	
	%	GWh	%	GWh	%	GWh	%	GWh
50 km	1.0141	29.6680	1.0989	37.0240	1.1615	43.4221	1.2079	48.7569
100 km	1.1551	33.7926	1.2532	42.2227	1.3256	49.5580	1.3794	55.6762
150 km	1.2964	37.9281	1.4078	47.4320	1.4900	55.7041	1.5510	62.6051
200 km	1.4382	42.0748	1.5627	52.6520	1.6546	61.8603	1.7229	69.5436
250 km	1.5803	46.2325	1.7179	57.8826	1.8196	68.0267	1.8951	76.4917
300 km	1.7228	50.4012	1.8735	63.1240	1.9848	74.2032	2.0674	83.4493

3xMonopolar 250 MW								
Transmission Distance	8 m/s		9 m/s		10 m/s		11 m/s	
	%	GWh	%	GWh	%	GWh	%	GWh
50 km	0.8190	23.9615	0.9103	30.6702	0.9798	36.6292	1.0324	41.6697
100 km	0.9292	27.1843	1.0349	34.8691	1.1154	41.6993	1.1763	47.4794
150 km	1.0398	30.4208	1.1600	39.0827	1.2514	46.7849	1.3206	53.3047
200 km	1.1509	33.6710	1.2855	43.3111	1.3878	51.8857	1.4653	59.1457
250 km	1.2625	36.9348	1.4114	47.5542	1.5247	57.0019	1.6104	65.0023
300 km	1.3745	40.2124	1.5378	51.8121	1.6619	62.1334	1.7559	70.8745

Monopolar 600 + Monopolar 130 MW								
Transmission Distance	8 m/s		9 m/s		10 m/s		11 m/s	
	%	GWh	%	GWh	%	GWh	%	GWh
50 km	1.2062	35.2874	1.2600	42.4528	1.2987	48.5549	1.3270	53.5646
100 km	1.3773	40.2944	1.4396	48.5040	1.4844	55.4969	1.5172	61.2389
150 km	1.5487	45.3084	1.6194	54.5620	1.6703	62.4453	1.7075	68.9193
200 km	1.7203	50.3293	1.7994	60.6266	1.8563	69.4002	1.8979	76.6059
250 km	1.8922	55.3573	1.9796	66.6981	2.0425	76.3615	2.0885	84.2986
300 km	2.0643	60.3923	2.1600	72.7762	2.2289	83.3293	2.2792	91.9974

Windfarm rated at 800 MW

Monopolar 500 + Monopolar 300 MW								
Transmission Distance	8 m/s		9 m/s		10 m/s		11 m/s	
	%	GWh	%	GWh	%	GWh	%	GWh
50 km	1.0945	36.6027	1.1798	45.4330	1.2425	53.0840	1.2887	59.4416
100 km	1.2481	41.7398	1.3468	51.8643	1.4193	60.6398	1.4728	67.9336
150 km	1.4021	46.8876	1.5141	58.3054	1.5964	68.2045	1.6571	76.4338
200 km	1.5563	52.0461	1.6816	64.7565	1.7736	75.7784	1.8416	84.9424
250 km	1.7109	57.2152	1.8494	71.2176	1.9511	83.3614	2.0262	93.4592
300 km	1.8658	62.3951	2.0175	77.6886	2.1288	90.9535	2.2111	101.9843

2xMonopolar 440 MW								
Transmission Distance	8 m/s		9 m/s		10 m/s		11 m/s	
	%	GWh	%	GWh	%	GWh	%	GWh
50 km	0.9511	31.8069	1.0354	39.8704	1.0979	46.9069	1.1444	52.7838
100 km	1.0822	36.1908	1.1797	45.4281	1.2520	53.4925	1.3058	60.2302
150 km	1.2137	40.5889	1.3244	50.9997	1.4065	60.0917	1.4675	67.6897
200 km	1.3457	45.0012	1.4694	56.5853	1.5613	66.7045	1.6296	75.1623
250 km	1.4780	49.4276	1.6149	62.1848	1.7164	73.3308	1.7918	82.6480
300 km	1.6108	53.8681	1.7606	67.7983	1.8718	79.9706	1.9544	90.1467

Monopolar 600 + Monopolar 250 MW								
Transmission Distance	8 m/s		9 m/s		10 m/s		11 m/s	
	%	GWh	%	GWh	%	GWh	%	GWh
50 km	1.0686	35.7368	1.1423	43.9895	1.1963	51.1108	1.2360	57.0087
100 km	1.2182	40.7379	1.3035	50.1940	1.3659	58.3566	1.4118	65.1187
150 km	1.3681	45.7503	1.4649	56.4095	1.5357	65.6129	1.5878	73.2386
200 km	1.5183	50.7741	1.6266	62.6360	1.7058	72.8798	1.7641	81.3686
250 km	1.6689	55.8091	1.7886	68.8735	1.8761	80.1572	1.9406	89.5086
300 km	1.8198	60.8555	1.9508	75.1219	2.0467	87.4451	2.1173	97.6587

Windfarm rated at 900 MW

3x Monopolar 300 MW								
Transmission Distance	8 m/s		9 m/s		10 m/s		11 m/s	
	%	GWh	%	GWh	%	GWh	%	GWh
50 km	0.9504	35.7602	1.0545	45.6851	1.1332	54.4661	1.1923	61.8618
100 km	1.0811	40.6782	1.2017	52.0605	1.2928	62.1359	1.3612	70.6249
150 km	1.2121	45.6093	1.3491	58.4489	1.4526	69.8184	1.5303	79.3999
200 km	1.3435	50.5537	1.4969	64.8505	1.6127	77.5134	1.6997	88.1868
250 km	1.4753	55.5112	1.6450	71.2651	1.7731	85.2210	1.8693	96.9857
300 km	1.6074	60.4820	1.7933	77.6929	1.9337	92.9412	2.0391	105.7965

Monopolar 600 + Monopolar 300 MW								
Transmission Distance	8 m/s		9 m/s		10 m/s		11 m/s	
	%	GWh	%	GWh	%	GWh	%	GWh
50 km	1.1116	41.8282	1.1937	51.7156	1.2539	60.2643	1.2982	67.3559
100 km	1.2679	47.7093	1.3629	59.0454	1.4325	68.8501	1.4838	76.9855
150 km	1.4245	53.6021	1.5323	66.3860	1.6113	77.4456	1.6696	86.6241
200 km	1.5814	59.5064	1.7020	73.7374	1.7904	86.0511	1.8555	96.2716
250 km	1.7386	65.4223	1.8720	81.0995	1.9696	94.6663	2.0417	105.9281
300 km	1.8962	71.3497	2.0421	88.4723	2.1491	103.2914	2.2279	115.5936

Monopolar 500 + Monopolar 440 MW								
Transmission Distance	8 m/s		9 m/s		10 m/s		11 m/s	
	%	GWh	%	GWh	%	GWh	%	GWh
50 km	1.0157	38.2186	1.1031	47.7882	1.1675	56.1151	1.2153	63.0516
100 km	1.1569	43.5330	1.2580	54.5013	1.3326	64.0493	1.3878	72.0053
150 km	1.2985	48.8615	1.4133	61.2280	1.4980	71.9963	1.5606	80.9710
200 km	1.4405	54.2042	1.5689	67.9682	1.6636	79.9561	1.7337	89.9488
250 km	1.5829	59.5610	1.7248	74.7221	1.8294	87.9288	1.9069	98.9387
300 km	1.7256	64.9320	1.8810	81.4895	1.9956	95.9143	2.0804	107.9406

Windfarm rated at 1000 MW

2x Monopolar 500 MW								
Transmission Distance	8 m/s		9 m/s		10 m/s		11 m/s	
	%	GWh	%	GWh	%	GWh	%	GWh
50 km	1.0656	44.5689	1.1555	55.6274	1.2215	65.2236	1.2700	73.1945
100 km	1.2147	50.8039	1.3187	63.4836	1.3950	74.4906	1.4512	83.6360
150 km	1.3641	57.0531	1.4822	71.3530	1.5688	83.7699	1.6326	94.0886
200 km	1.5139	63.3165	1.6459	79.2357	1.7428	93.0613	1.8141	104.5523
250 km	1.6640	69.5942	1.8099	87.1317	1.9170	102.3650	1.9959	115.0271
300 km	1.8144	75.8861	1.9742	95.0409	2.0915	111.6807	2.1778	125.5131

Monopolar 440 + 600 MW								
Transmission Distance	8 m/s		9 m/s		10 m/s		11 m/s	
	%	GWh	%	GWh	%	GWh	%	GWh
50 km	1.0263	42.9249	1.1127	53.5662	1.1762	62.8070	1.2230	70.4861
100 km	1.1692	48.9017	1.2692	61.0986	1.3427	71.6946	1.3968	80.5023
150 km	1.3125	54.8939	1.4259	68.6458	1.5094	80.5962	1.5708	90.5315
200 km	1.4561	60.9015	1.5830	76.2078	1.6763	89.5116	1.7451	100.5738
250 km	1.6002	66.9245	1.7404	83.7845	1.8435	98.4409	1.9196	110.6292
300 km	1.7445	72.9630	1.8981	91.3760	2.0110	107.3842	2.0943	120.6976

Monopolar 500 + 600 MW								
Transmission Distance	8 m/s		9 m/s		10 m/s		11 m/s	
	%	GWh	%	GWh	%	GWh	%	GWh
50 km	0.9468	39.6002	1.0312	49.6418	1.0936	58.3941	1.1397	65.6854
100 km	1.0773	45.0548	1.1748	56.5580	1.2470	66.5887	1.3004	74.9476
150 km	1.2081	50.5273	1.3189	63.4918	1.4008	74.8004	1.4614	84.2264
200 km	1.3394	56.0176	1.4633	70.4431	1.5549	83.0292	1.6227	93.5217
250 km	1.4711	61.5257	1.6080	77.4121	1.7093	91.2751	1.7843	102.8336
300 km	1.6032	67.0517	1.7532	84.3986	1.8641	99.5381	1.9462	112.1620

2x Monopolar 600 MW								
Transmission Distance	8 m/s		9 m/s		10 m/s		11 m/s	
	%	GWh	%	GWh	%	GWh	%	GWh
50 km	0.8280	34.6314	0.9068	43.6563	0.9657	51.5647	1.0094	58.1763
100 km	0.9398	39.3057	1.0310	49.6324	1.0991	58.6867	1.1497	66.2593
150 km	1.0521	44.0015	1.1556	55.6305	1.2328	65.8309	1.2903	74.3642
200 km	1.1649	48.7186	1.2806	61.6506	1.3670	72.9970	1.4313	82.4912
250 km	1.2782	53.4572	1.4061	67.6925	1.5017	80.1852	1.5727	90.6401
300 km	1.3920	58.2173	1.5321	73.7564	1.6367	87.3955	1.7145	98.8109

Appendix B

Unavailability and Non-Transmitted Energy due to Forced Outages for HVDC VSC Transmission Systems

Windfarm rated at 400 MW

2x220 MW CS, 2x220 MW CP								
Transmission Distance	8 m/s		9 m/s		10 m/s		11 m/s	
	%	GWh	%	GWh	%	GWh	%	GWh
50 km	5.1217	85.5675	5.5970	107.7378	5.9487	127.1166	6.2112	143.3565
100 km	5.4124	90.4248	5.9107	113.7773	6.2794	134.1851	6.5547	151.2845
150 km	5.7048	95.3101	6.2259	119.8443	6.6115	141.2801	6.8993	159.2380
200 km	5.9989	100.2234	6.5425	125.9387	6.9447	148.4016	7.2450	167.2170
250 km	6.2946	105.1646	6.8605	132.0605	7.2792	155.5497	7.5918	175.2215
300 km	6.5921	110.1337	7.1800	138.2098	7.6150	162.7244	7.9397	183.2515

500 MW CS, 1x500 MW CP								
Transmission Distance	8 m/s		9 m/s		10 m/s		11 m/s	
	%	GWh	%	GWh	%	GWh	%	GWh
50 km	8.3322	139.2062	8.3322	160.3888	8.3322	178.0503	8.3322	192.3099
100 km	8.7784	146.6609	8.7784	168.9778	8.7784	187.5852	8.7784	102.6083
150 km	9.2246	154.1155	9.2246	177.5669	9.2246	197.1200	9.2246	212.9067
200 km	9.6708	161.5702	9.6708	186.1559	9.6708	206.6548	9.6708	223.2052
250 km	10.1170	169.0249	10.1170	194.7449	10.1170	216.1896	10.1170	233.5036
300 km	10.5632	176.4795	10.5632	203.3339	10.5632	225.7245	10.5632	243.8021

2x220 MW CS, 1x500 MW CP								
Transmission Distance	8 m/s		9 m/s		10 m/s		11 m/s	
	%	GWh	%	GWh	%	GWh	%	GWh
50 km	5.2572	87.8326	5.7073	109.8609	6.0402	129.0737	6.2888	145.1481
100 km	5.6819	94.9270	6.1299	117.9960	6.4614	138.0728	6.7088	154.8421
150 km	6.1065	102.0214	6.5525	126.1311	6.8825	147.0718	7.1289	164.5362
200 km	6.5311	109.1158	6.9751	134.2663	7.3036	156.0709	7.5489	174.2302
250 km	6.9558	116.2102	7.3978	142.4014	7.7248	165.0700	7.9689	183.9243
300 km	7.3804	123.3046	7.8204	150.5365	8.1459	174.0690	8.3889	193.6183

Windfarm rated at 500 MW

350+220 MW CS, 350+220 MW CP								
Transmission Distance	8 m/s		9 m/s		10 m/s		11 m/s	
	%	GWh	%	GWh	%	GWh	%	GWh
50 km	4.9799	104.0072	5.4191	130.3969	5.7428	153.3870	5.9838	172.6000
100 km	5.2638	109.9360	5.7242	137.7392	6.0636	161.9558	6.3163	182.1904
150 km	5.5494	115.9013	6.0309	145.1182	6.3858	170.5606	6.6500	191.8160
200 km	5.8368	121.9031	6.3391	152.5337	6.7093	179.2015	6.9849	201.4770
250 km	6.1259	127.9413	6.6488	159.9857	7.0342	187.8784	7.3211	211.1733
300 km	6.4167	134.0161	6.9600	167.4743	7.3604	196.5913	7.6584	220.9049

2x350 MW CS, 2x350 MW CP								
Transmission Distance	8 m/s		9 m/s		10 m/s		11 m/s	
	%	GWh	%	GWh	%	GWh	%	GWh
50 km	3.3126	69.1850	3.6672	88.2411	3.9348	105.0958	4.1372	119.3352
100 km	3.5157	73.4275	3.8875	93.5422	4.1680	111.3262	4.3802	126.3463
150 km	3.7215	77.7247	4.1102	98.9018	4.4036	117.6177	4.6255	133.4205
200 km	3.9299	82.0766	4.3354	104.3199	4.6415	123.9705	4.8729	140.5578
250 km	4.1408	86.4831	4.5630	109.7966	4.8816	130.3846	5.1226	147.7581
300 km	4.3545	90.9443	4.7930	115.3318	5.1240	136.8598	5.3744	155.0215

1x500 MW CS,1x500 MW CP								
Transmission Distance	8 m/s		9 m/s		10 m/s		11 m/s	
	%	GWh	%	GWh	%	GWh	%	GWh
50 km	8.3322	174.0211	8.3322	200.4937	8.3322	222.5482	8.3322	240.3392
100 km	8.7784	183.3402	8.7784	211.2304	8.7784	234.4659	8.7784	253.2096
150 km	9.2246	192.6592	9.2246	221.9671	9.2246	246.3837	9.2246	266.0801
200 km	9.6708	201.9783	9.6708	232.7038	9.6708	258.3014	9.6708	278.9506
250 km	10.1170	211.2974	10.1170	243.4405	10.1170	270.2191	10.1170	291.8210
300 km	10.5632	220.6164	10.5632	254.1772	10.5632	282.1369	10.5632	304.6915

350+220 MW CS, 1x500 MW CP								
Transmission Distance	8 m/s		9 m/s		10 m/s		11 m/s	
	%	GWh	%	GWh	%	GWh	%	GWh
50 km	5.1230	106.9962	5.5388	133.2785	5.8453	156.1258	6.0735	175.1880
100 km	5.5483	115.8775	5.9622	143.4659	6.2673	167.3972	6.4945	187.3309
150 km	5.9735	124.7588	6.3856	153.6534	6.6893	178.6686	6.9155	199.4739
200 km	6.3987	133.6400	6.8090	163.8409	7.1113	189.9400	7.3364	211.6169
250 km	6.8240	142.5213	7.2323	174.0283	7.5333	201.2114	7.7574	223.7598
300 km	7.2492	151.4026	7.6557	184.2158	7.9554	212.4828	8.1784	235.9028

2x350 MW CS, 1x500 MW CP								
Transmission Distance	8 m/s		9 m/s		10 m/s		11 m/s	
	%	GWh	%	GWh	%	GWh	%	GWh
50 km	3.5444	74.0261	3.8801	93.3649	4.1335	110.4031	4.3251	124.7562
100 km	3.9767	83.0551	4.3109	103.7313	4.5632	121.8794	4.7539	137.1252
150 km	4.4090	92.0842	4.7417	114.0976	4.9928	133.3557	5.1827	149.4942
200 km	4.8413	101.1132	5.1725	124.4640	5.4225	144.8320	5.6116	161.8632
250 km	5.2737	110.1422	5.6033	134.8304	5.8522	156.3084	6.0404	174.2322
300 km	5.7060	119.1713	6.0341	145.1967	6.2819	167.7847	6.4692	186.6012

Windfarm rated at 600 MW

2x350 MW CS, 2x350 MW CP								
Transmission Distance	8 m/s		9 m/s		10 m/s		11 m/s	
	%	GWh	%	GWh	%	GWh	%	GWh
50 km	4.6683	117.0246	5.1160	147.7346	5.4490	174.6304	5.6985	197.1987
100 km	4.9370	123.7624	5.4064	156.1222	5.7556	184.4560	6.0171	208.2264
150 km	5.2077	130.5481	5.6986	164.5583	6.0637	194.3297	6.3372	219.3015
200 km	5.4803	137.3817	5.9924	173.0428	6.3733	204.2516	6.6586	230.4242
250 km	5.7548	144.2632	6.2879	181.5757	6.6844	214.2216	6.9814	241.5944
300 km	6.0313	151.1926	6.5850	190.1571	6.9969	224.2399	7.3055	252.8121

500+220 MW CS, 500+220 MW CP								
Transmission Distance	8 m/s		9 m/s		10 m/s		11 m/s	
	%	GWh	%	GWh	%	GWh	%	GWh
50 km	4.8903	122.5900	5.2574	151.8176	5.5266	177.1193	5.7262	198.1594
100 km	5.1698	129.5974	5.5547	160.4030	5.8370	187.0654	6.0463	209.2336
150 km	5.4511	136.6497	5.8536	169.0347	6.1488	197.0583	6.3676	220.3548
200 km	5.7342	143.7470	6.1541	177.7126	6.4621	207.0982	6.6904	231.5229
250 km	6.0192	150.8892	6.4562	186.4369	6.7768	217.1848	7.0144	242.7381
300 km	6.3059	158.0765	6.7599	195.2074	7.0930	227.3184	7.3399	254.0004

Windfarm rated at 700 MW

2x350 MW CS, 2x350 MW CP								
Transmission Distance	8 m/s		9 m/s		10 m/s		11 m/s	
	%	GWh	%	GWh	%	GWh	%	GWh
50 km	5.7515	168.2668	6.2487	210.5379	6.6145	247.2892	6.8856	277.9273
100 km	6.0728	177.6649	6.5940	222.1725	6.9775	260.8611	7.2617	293.1101
150 km	6.3953	187.1024	6.9404	233.8437	7.3414	274.4666	7.6386	308.3233
200 km	6.7193	196.5792	7.2879	245.5514	7.7062	288.1055	8.0163	323.5670
250 km	7.0445	206.0953	7.6365	257.2958	8.0720	301.7780	8.3947	338.8411
300 km	7.3712	215.6509	7.9861	269.0768	8.4386	315.4839	8.7738	354.1457

500+220 MW CS, 500+220 MW CP								
Transmission Distance	8 m/s		9 m/s		10 m/s		11 m/s	
	%	GWh	%	GWh	%	GWh	%	GWh
50 km	5.9138	173.0155	6.3410	213.6472	6.6534	248.7421	6.8837	277.8510
100 km	6.2429	182.6435	6.6908	225.4324	7.0183	262.3845	7.2597	293.0301
150 km	6.5733	192.3084	7.0416	237.2525	7.3840	276.0595	7.6365	308.2397
200 km	6.9049	202.0102	7.3935	249.1076	7.7507	289.7673	8.0141	323.4798
250 km	7.2378	211.7489	7.7463	260.9976	8.1182	303.5078	8.3924	338.7503
300 km	7.5719	221.5245	8.1003	272.9227	8.4866	317.2810	8.7715	354.0514

Windfarm rated at 800 MW

2x350+220 MW CS,2x 350+220 MW CP								
Transmission Distance	8 m/s		9 m/s		10 m/s		11 m/s	
	%	GWh	%	GWh	%	GWh	%	GWh
50 km	3.5836	119.8421	4.0270	155.0715	4.3641	186.4538	4.6186	213.0303
100 km	3.7989	127.0415	4.2654	164.2522	4.6199	197.3845	4.8875	225.4344
150 km	4.0166	134.3207	4.5061	173.5218	4.8780	208.4106	5.1586	237.9386
200 km	4.2366	141.6798	4.7492	182.8802	5.1383	219.5320	5.4319	250.5426
250 km	4.4591	149.1188	4.9945	192.3273	5.4008	230.7484	5.7073	263.2464
300 km	4.6839	156.6377	5.2421	201.8632	5.6656	242.0599	5.9849	276.0496

3x350 MW CS, 3x350 MW CP								
Transmission Distance	8 m/s		9 m/s		10 m/s		11 m/s	
	%	GWh	%	GWh	%	GWh	%	GWh
50 km	2.0508	68.5832	2.3288	89.6760	2.5438	108.6820	2.7083	124.9194
100 km	2.1926	73.3253	2.4866	95.7535	2.7138	115.9469	2.8876	133.1893
150 km	2.3377	78.1761	2.6478	101.9598	2.8872	123.3568	3.0703	141.6173
200 km	2.4860	83.1358	2.8123	108.2947	3.0641	130.9116	3.2565	150.2029
250 km	2.6376	88.2043	2.9801	114.7581	3.2443	138.6109	3.4460	158.9460
300 km	2.7924	93.3817	3.1513	121.3497	3.4279	146.4544	3.6390	167.8459

500+350 MW CS, 500+350 MW CP								
Transmission Distance	8 m/s		9 m/s		10 m/s		11 m/s	
	%	GWh	%	GWh	%	GWh	%	GWh
50 km	5.3779	179.8447	5.8489	225.2285	6.1968	264.7569	6.4548	297.7264
100 km	5.6810	189.9823	6.1748	237.7801	6.5396	279.4028	6.8101	314.1141
150 km	5.9857	200.1714	6.5021	250.3817	6.8835	294.0964	7.1664	330.5469
200 km	6.2919	210.4119	6.8306	263.0331	7.2285	308.8374	7.5237	347.0249
250 km	6.5997	220.7040	7.1605	275.7343	7.5747	323.6261	7.8819	363.5480
300 km	6.9090	231.0476	7.4916	288.4854	7.9219	338.4623	8.2411	380.1163

Windfarm rated at 900 MW

3x350 MW CS, 3x350 MW CP								
Transmission Distance	8 m/s		9 m/s		10 m/s		11 m/s	
	%	GWh	%	GWh	%	GWh	%	GWh
50 km	3.3146	124.7216	3.7517	162.5335	4.0857	196.3693	4.3378	225.0618
100 km	3.5170	132.3400	3.9771	172.2990	4.3284	208.0376	4.5936	238.3336
150 km	3.7220	140.0543	4.2050	182.1719	4.5736	219.8219	4.8518	251.7278
200 km	3.9296	147.8644	4.4353	192.1523	4.8212	231.7222	5.1123	265.2440
250 km	4.1397	155.7704	4.6682	202.2400	5.0712	243.7382	5.3752	278.8822
300 km	4.3524	163.7723	4.9035	212.4350	5.3236	255.8698	5.6404	292.6420

2x500 MW CS, 2x500 MW CP								
Transmission Distance	8 m/s		9 m/s		10 m/s		11 m/s	
	%	GWh	%	GWh	%	GWh	%	GWh
50 km	5.0030	188.2540	5.4670	236.8494	5.8114	279.3115	6.0671	314.7845
100 km	5.2880	198.9777	5.7745	250.1696	6.1355	294.8903	6.4037	332.2443
150 km	5.5747	209.7667	6.0835	263.5544	6.4609	310.5323	6.7414	349.7653
200 km	5.8632	220.6210	6.3939	277.0040	6.7877	326.2374	7.0802	367.3476
250 km	6.1534	231.5406	6.7058	290.5183	7.1158	342.0058	7.4203	384.9912
300 km	6.4453	242.5255	7.0193	304.0973	7.4452	357.8372	7.7615	402.6960

2x350+220 MW CS,2x 350+220 MW CP								
Transmission Distance	8 m/s		9 m/s		10 m/s		11 m/s	
	%	GWh	%	GWh	%	GWh	%	GWh
50 km	4.8226	181.4670	5.3920	233.5964	5.8206	5.8206	314.7845	318.6602
100 km	5.0970	191.7913	5.6949	246.7203	6.1449	6.1449	332.2443	336.3117
150 km	5.3730	202.1779	5.9993	259.9071	6.4705	6.4705	349.7653	354.0228
200 km	5.6507	212.6270	6.3051	273.1569	6.7973	6.7973	367.3476	371.7935
250 km	5.9301	223.1388	6.6124	286.4696	7.1255	7.1255	384.9912	389.6238
300 km	6.2111	233.7132	6.9211	299.8454	7.4549	7.4549	402.6960	407.5136

Windfarm rated at 1000 MW

3x350 MW CS, 3x350 MW CP								
Transmission Distance	8 m/s		9 m/s		10 m/s		11 m/s	
	%	GWh	%	GWh	%	GWh	%	GWh
50 km	4.4992	188.1713	5.0447	242.8534	5.4552	291.2934	5.7616	332.0549
100 km	4.7576	198.9809	5.3308	256.6274	5.7620	307.6749	6.0838	350.6207
150 km	5.0179	209.8659	5.6185	270.4800	6.0702	324.1361	6.4073	369.2660
200 km	5.2799	220.8264	5.9079	284.4113	6.3800	340.6769	6.7322	387.9907
250 km	5.5438	231.8627	6.1989	298.4213	6.6913	357.2973	7.0585	406.7947
300 km	5.8095	242.9747	6.4916	312.5101	7.0040	373.9973	7.3861	425.6781

2x500 MW CS, 2x500 MW CP								
Transmission Distance	8 m/s		9 m/s		10 m/s		11 m/s	
	%	GWh	%	GWh	%	GWh	%	GWh
50 km	5.7191	239.1949	6.2174	299.3092	6.5830	351.5165	6.8522	394.9070
100 km	6.0388	252.5645	6.5612	315.8597	6.9445	370.8197	7.2267	416.4922
150 km	6.3598	265.9912	6.9061	332.4633	7.3069	390.1715	7.6020	438.1218
200 km	6.6822	279.4748	7.2521	349.1199	7.6702	409.5721	7.9781	459.7960
250 km	7.0060	293.0153	7.5992	365.8296	8.0345	429.0213	8.3550	481.5146
300 km	7.3311	306.6129	7.9474	382.5924	8.3996	448.5192	8.7326	503.2776

Appendix C

Unavailability and Non-Transmitted Energy due to Forced Outages for HVAC Transmission Systems

Windfarm rated at 400 MW

Transmission Voltage: 132 kV								
Transmission Distance	8 m/s		9 m/s		10 m/s		11 m/s	
	%	GWh	%	GWh	%	GWh	%	GWh
50 km	1.8128	30.2862	1.8550	35.7083	1.8866	40.3141	1.9102	44.0889
100 km	1.9510	32.5947	2.0072	38.6373	2.0490	43.7859	2.0804	48.0162
150 km	2.1309	35.6016	2.2030	42.4060	2.2563	48.2147	2.2961	52.9946
200 km	2.3695	39.5878	2.4600	47.3527	2.5264	53.9865	2.5757	59.4487
250 km	1.7391	29.0558	1.7882	34.4223	1.8265	39.0298	1.8559	42.8341
300 km	2.3896	39.9235	2.5162	48.4346	2.6121	55.8174	2.6848	61.9663

Transmission Voltage: 220 kV								
Transmission Distance	8 m/s		9 m/s		10 m/s		11 m/s	
	%	GWh	%	GWh	%	GWh	%	GWh
50 km	1.3553	22.6426	1.3567	26.1160	1.3579	29.0162	1.3587	31.3600
100 km	1.4031	23.4411	1.4133	27.2058	1.4215	30.3758	1.4278	32.9537
150 km	1.5329	25.6106	1.5629	30.0856	1.5863	33.8979	1.6043	37.0281
200 km	1.8276	30.5344	1.8917	36.4135	1.9403	41.4623	1.9772	45.6350
250 km	1.5454	25.8192	1.5808	30.4302	1.6086	34.3742	1.6299	37.6195
300 km	-	-	-	-	-	-	-	-

Transmission Voltage: 400 kV								
Transmission Distance	8 m/s		9 m/s		10 m/s		11 m/s	
	%	GWh	%	GWh	%	GWh	%	GWh
50 km	1.5562	25.9995	1.5562	29.9557	1.5562	33.2544	1.5562	35.9176
100 km	1.7793	29.7268	1.7793	34.2502	1.7793	38.0218	1.7793	41.0668
150 km	2.0024	33.4541	2.0024	38.5447	2.0024	42.7892	2.0024	46.2160
200 km	1.5030	25.1107	1.5866	30.5400	1.6502	35.2629	1.6986	39.2046
250 km	-	-	-	-	-	-	-	-
300 km	-	-	-	-	-	-	-	-

Modified Case A

395 MW windfarm , Transmission Voltage: 220 kV, Transmission Distance 50 km				
Need for one 220 kV cable (2 needed in the non-modified version above)				
Average wind speed	8 m/s	9 m/s	10 m/s	11 m/s
Unavailability (%)	2.0846	2.0846	2.0846	2.0846

Windfarm rated at 500 MW

Transmission Voltage: 132 kV								
Transmission Distance	8 m/s		9 m/s		10 m/s		11 m/s	
	%	GWh	%	GWh	%	GWh	%	GWh
50 km	1.4940	31.2037	1.5038	36.1842	1.5115	40.3707	1.5175	43.7727
100 km	1.5466	32.3011	1.5645	37.6464	1.5784	42.1582	1.5890	45.8330
150 km	1.6627	34.7272	1.6987	40.8761	1.7265	46.1140	1.7477	50.4110
200 km	1.8672	38.9973	1.9345	46.5486	1.9863	53.0525	2.0259	58.4367
250 km	2.2627	47.2583	2.3720	57.0755	2.4544	65.5554	2.5167	72.5936
300 km	2.0370	42.5436	2.1329	51.3222	2.2067	58.9390	2.2631	65.2769

Transmission Voltage: 220 kV								
Transmission Distance	8 m/s		9 m/s		10 m/s		11 m/s	
	%	GWh	%	GWh	%	GWh	%	GWh
50 km	1.5080	31.4955	1.5333	36.8957	1.5528	41.4734	1.5676	45.2172
100 km	1.6118	33.6637	1.6497	39.6957	1.6785	44.8319	1.7004	49.0477
150 km	1.7920	37.4267	1.8496	44.5056	1.8929	50.5589	1.9256	55.5446
200 km	2.1318	44.5238	2.2160	53.3230	2.2783	60.8514	2.3247	67.0558
250 km	2.0723	43.2816	2.1736	52.3030	2.2504	60.1071	2.3086	66.5912
300 km	-	-	-	-	-	-	-	-

Transmission Voltage: 400 kV								
Transmission Distance	8 m/s		9 m/s		10 m/s		11 m/s	
	%	GWh	%	GWh	%	GWh	%	GWh
50 km	1.5562	32.5018	1.5562	37.4461	1.5562	41.5652	1.5562	44.8880
100 km	1.7793	37.1614	1.7793	42.8144	1.7793	47.5241	1.7793	51.3232
150 km	2.0024	41.8209	2.0024	48.1828	2.0024	53.4829	2.0024	57.7585
200 km	1.2294	25.6757	1.2832	30.8782	1.3248	35.3848	1.3565	39.1279
250 km	-	-	-	-	-	-	-	-
300 km	-	-	-	-	-	-	-	-

Modified Case B

475 MW windfarm , Transmission Voltage: 132 kV, Transmission Distance 50 km				
Need for two 132 kV cable (3 needed in the non-modified version above)				
Average wind speed	8 m/s	9 m/s	10 m/s	11 m/s
Unavailability (%)	1.9293	1.9765	2.0111	2.0367

Windfarm rated at 600 MW

Transmission Voltage: 132 kV								
Transmission Distance	8 m/s		9 m/s		10 m/s		11 m/s	
	%	GWh	%	GWh	%	GWh	%	GWh
50 km	1.4044	35.2058	1.4932	43.1197	1.5597	49.9856	1.6097	55.7048
100 km	1.5151	37.9795	1.6185	46.7387	1.6961	54.3583	1.7546	60.7180
150 km	1.6912	42.3965	1.8155	52.4277	1.9087	61.1692	1.9787	68.4752
200 km	1.9593	49.1165	2.1130	61.0177	2.2278	71.3970	2.3140	80.0780
250 km	1.5472	38.7859	1.6616	47.9814	1.7480	56.0210	1.8136	62.7611
300 km	1.4425	36.1605	1.5435	44.5716	1.6202	51.9253	1.6812	58.1800

Transmission Voltage: 220 kV								
Transmission Distance	8 m/s		9 m/s		10 m/s		11 m/s	
	%	GWh	%	GWh	%	GWh	%	GWh
50 km	1.4015	35.1329	1.4844	42.8664	1.5460	49.5473	1.5921	55.0954
100 km	1.5369	38.5285	1.6347	47.2060	1.7073	54.7158	1.7616	60.9609
150 km	1.7568	44.0386	1.8718	54.0537	1.9568	62.7131	2.0202	69.9096
200 km	1.2268	30.7543	1.2935	37.3521	1.3443	43.0833	1.3835	47.8761
250 km	1.3631	34.1716	1.4527	41.9488	1.5205	48.7279	1.5721	54.4022
300 km	-	-	-	-	-	-	-	-

Transmission Voltage: 400 kV								
Transmission Distance	8 m/s		9 m/s		10 m/s		11 m/s	
	%	GWh	%	GWh	%	GWh	%	GWh
50 km	1.2978	32.5345	1.3470	38.8985	1.3831	44.3265	1.4099	48.7902
100 km	1.5198	38.0986	1.5689	45.3050	1.6049	51.4339	1.6316	56.4626
150 km	1.7418	43.6628	1.7907	51.7114	1.8267	58.5412	1.8533	64.1350
200 km	0.7317	18.3429	0.7959	22.9820	0.8437	27.0400	0.8797	30.4434
250 km	-	-	-	-	-	-	-	-
300 km	-	-	-	-	-	-	-	-

Windfarm rated at 700 MW

Transmission Voltage: 132 kV								
Transmission Distance	8 m/s		9 m/s		10 m/s		11 m/s	
	%	GWh	%	GWh	%	GWh	%	GWh
50 km	1.3559	39.6697	1.4978	50.4650	1.6032	59.9366	1.6818	67.8833
100 km	0.9830	28.7587	1.0765	36.2718	1.1460	42.8426	1.1974	48.3329
150 km	1.0851	31.7453	1.2001	40.4362	1.2864	48.0926	1.3511	54.5368
200 km	1.3325	38.9826	1.4834	49.9801	1.5971	59.7105	1.6829	67.9275
250 km	1.7888	52.3335	1.9982	67.3237	2.1559	80.5989	2.2745	91.8054
300 km	1.8509	54.1511	2.0829	70.1802	2.2592	84.4633	2.3925	96.5686

Transmission Voltage: 220 kV								
Transmission Distance	8 m/s		9 m/s		10 m/s		11 m/s	
	%	GWh	%	GWh	%	GWh	%	GWh
50 km	1.2912	37.7755	1.4182	47.7836	1.5119	56.5242	1.5815	63.8344
100 km	1.4585	42.6704	1.6004	53.9234	1.7050	63.7437	1.7826	71.9524
150 km	0.9444	27.6292	1.0379	34.9701	1.1072	41.3948	1.1589	46.7757
200 km	1.3021	38.0955	1.4512	48.8962	1.5635	58.4523	1.6478	66.5131
250 km	1.5929	46.6021	1.7843	60.1184	1.9291	72.1203	2.0382	82.2686
300 km	-	-	-	-	-	-	-	-

Transmission Voltage: 400 kV								
Transmission Distance	8 m/s		9 m/s		10 m/s		11 m/s	
	%	GWh	%	GWh	%	GWh	%	GWh
50 km	1.3021	38.0935	1.3502	45.4928	1.3856	51.8017	1.4118	56.9849
100 km	1.5240	44.5870	1.5721	52.9674	1.6074	60.0926	1.6335	65.9338
150 km	0.7905	23.1265	0.8596	28.9634	0.9115	34.0780	0.9505	38.3667
200 km	1.1835	34.6248	1.3176	44.3938	1.4199	53.0826	1.4976	60.4482
250 km	-	-	-	-	-	-	-	-
300 km	-	-	-	-	-	-	-	-

Modified Case C

680 MW windfarm , Transmission Voltage: 220 kV, Transmission Distance 150 km				
Need for two 220 kV cable (3 needed in the non-modified version above)				
Average wind speed	8 m/s	9 m/s	10 m/s	11 m/s
Unavailability (%)	1.6281	1.7857	1.9017	1.9877

Windfarm rated at 800 MW

Transmission Voltage: 132 kV								
Transmission Distance	8 m/s		9 m/s		10 m/s		11 m/s	
	%	GWh	%	GWh	%	GWh	%	GWh
50 km	1.0980	36.7200	1.2157	46.8139	1.3036	55.6965	1.3694	63.1611
100 km	1.1888	39.7545	1.3209	50.8659	1.4201	60.6727	1.4945	68.9310
150 km	1.3553	45.3235	1.5133	58.2757	1.6324	69.7434	1.7219	79.4235
200 km	1.6620	55.5812	1.8574	71.5243	2.0044	85.6374	2.1146	97.5357
250 km	1.3987	46.7753	1.5663	60.3151	1.6934	72.3517	1.7895	82.5391
300 km	1.5799	52.8356	1.7775	68.4474	1.9281	82.3777	2.0423	94.1981

Transmission Voltage: 220 kV								
Transmission Distance	8 m/s		9 m/s		10 m/s		11 m/s	
	%	GWh	%	GWh	%	GWh	%	GWh
50 km	0.8936	29.8821	0.9816	37.7975	1.0464	44.7074	1.0945	50.4836
100 km	0.9574	32.0156	1.0583	40.7544	1.1340	48.4500	1.1905	54.9132
150 km	1.1433	38.2332	1.2718	48.9756	1.3684	58.4632	1.4408	66.4563
200 km	1.5670	52.4036	1.7446	67.1792	1.8774	80.2131	1.9768	91.1784
250 km	1.1817	39.5175	1.3205	50.8492	1.4259	60.9203	1.5056	69.4439
300 km	-	-	-	-	-	-	-	-

Transmission Voltage: 400 kV								
Transmission Distance	8 m/s		9 m/s		10 m/s		11 m/s	
	%	GWh	%	GWh	%	GWh	%	GWh
50 km	1.2955	43.3229	1.3446	51.7790	1.3808	58.9941	1.4075	64.9225
100 km	0.6599	22.0670	0.7099	27.3358	0.7467	31.9032	0.7740	35.6998
150 km	0.9197	30.7558	1.0079	38.8138	1.0743	45.8971	1.1239	51.8400
200 km	0.9540	31.9022	1.0570	40.7014	1.1360	48.5360	1.1962	55.1754
250 km	-	-	-	-	-	-	-	-
300 km	-	-	-	-	-	-	-	-

Modified Cases D, E

790 MW windfarm , Transmission Voltage: 220 kV, Transmission Distance 50 km				
Need for two 220 kV cable (3 needed in the non-modified version above)				
Average wind speed	8 m/s	9 m/s	10 m/s	11 m/s
Unavailability (%)	1.3437	1.4754	1.5725	1.6443

795 MW windfarm , Transmission Voltage: 400 kV, Transmission Distance 100 km				
Need for one 400 kV cable (2 needed in the non-modified version above)				
Average wind speed	8 m/s	9 m/s	10 m/s	11 m/s
Unavailability (%)	1.5134	1.5622	1.5982	1.6248

Windfarm rated at 900 MW

Transmission Voltage: 132 kV								
Transmission Distance	8 m/s		9 m/s		10 m/s		11 m/s	
	%	GWh	%	GWh	%	GWh	%	GWh
50 km	1.2554	47.2376	1.3941	60.3979	1.4979	71.9942	1.5754	1.5754
100 km	1.3979	52.6015	1.5559	67.4046	1.6742	80.4679	1.7626	1.7626
150 km	1.0241	38.5348	1.1284	48.8839	1.2057	57.9497	1.2630	1.2630
200 km	1.2924	48.6308	1.4416	62.4546	1.5544	74.7083	1.6392	1.6392
250 km	1.0535	39.6408	1.1628	50.3766	1.2441	59.7957	1.3043	1.3043
300 km	1.3027	49.0172	1.4645	63.4481	1.5882	76.3344	1.6818	1.6818

Transmission Voltage: 220 kV								
Transmission Distance	8 m/s		9 m/s		10 m/s		11 m/s	
	%	GWh	%	GWh	%	GWh	%	GWh
50 km	1.0125	38.0986	1.1188	48.4715	1.1981	57.5829	1.2571	65.2232
100 km	1.1191	42.1100	1.2421	53.8121	1.3342	64.1259	1.4030	72.7951
150 km	1.3453	50.6203	1.4965	64.8326	1.6097	77.3672	1.6942	87.8993
200 km	1.0325	38.8499	1.1470	49.6905	1.2331	59.2670	1.2977	67.3273
250 km	1.6101	60.5844	1.8124	78.5178	1.9660	94.4939	2.0820	108.0238
300 km	-	-	-	-	-	-	-	-

Transmission Voltage: 400 kV								
Transmission Distance	8 m/s		9 m/s		10 m/s		11 m/s	
	%	GWh	%	GWh	%	GWh	%	GWh
50 km	0.6635	24.9678	0.7137	30.9189	0.7506	36.0757	0.7778	40.3573
100 km	0.7514	28.2727	0.8160	35.3527	0.8644	41.5451	0.9005	46.7222
150 km	1.0476	39.4212	1.1475	49.7125	1.2220	58.7341	1.2776	66.2854
200 km	0.7551	28.4126	0.8239	35.6943	0.8757	42.0894	0.9143	47.4396
250 km	-	-	-	-	-	-	-	-
300 km	-	-	-	-	-	-	-	-

Modified Cases F

885 MW windfarm , Transmission Voltage: 400 kV, Transmission Distance 50 km				
Need for one 400 kV cable (2 needed in the non-modified version above)				
Average wind speed	8 m/s	9 m/s	10 m/s	11 m/s
Unavailability (%)	1.2863	1.3346	1.3701	1.3964

Windfarm rated at 1000 MW

Transmission Voltage: 132 kV								
Transmission Distance	8 m/s		9 m/s		10 m/s		11 m/s	
	%	GWh	%	GWh	%	GWh	%	GWh
50 km	0.9559	39.9810	1.0713	51.5749	1.1581	61.8416	1.2229	70.4789
100 km	1.0285	43.0142	1.1559	55.6474	1.2537	66.9428	1.3277	76.5168
150 km	1.2081	50.5285	1.3641	65.6668	1.4824	79.1572	1.5713	90.5602
200 km	1.5273	63.8766	1.7325	83.4046	1.8887	100.8507	2.0063	115.6280
250 km	1.3986	58.4943	1.5872	76.4068	1.7311	92.4377	1.8397	106.0248
300 km	1.0049	42.0275	1.1275	54.2776	1.2205	65.1715	1.2922	74.4745

Transmission Voltage: 220 kV								
Transmission Distance	8 m/s		9 m/s		10 m/s		11 m/s	
	%	GWh	%	GWh	%	GWh	%	GWh
50 km	1.0540	44.0810	1.1829	56.9443	1.2798	68.3403	1.3523	77.9368
100 km	1.2001	50.1931	1.3471	64.8514	1.4576	77.8328	1.5401	88.7580
150 km	1.4567	60.9231	1.6322	78.5772	1.7638	94.1833	1.8619	107.3029
200 km	1.2369	51.7331	1.3978	67.2914	1.5199	81.1607	1.6118	92.8890
250 km	1.1698	48.9248	1.3251	63.7932	1.4439	77.0996	1.5334	88.3737
300 km	-	-	-	-	-	-	-	-

Transmission Voltage: 400 kV								
Transmission Distance	8 m/s		9 m/s		10 m/s		11 m/s	
	%	GWh	%	GWh	%	GWh	%	GWh
50 km	0.6555	27.4159	0.7234	34.8259	0.7749	41.3802	0.8136	46.8913
100 km	0.7644	31.9715	0.8486	40.8535	0.9128	48.7394	0.9612	55.3956
150 km	1.0850	45.3799	1.2009	57.8118	1.2879	68.7696	1.3528	77.9642
200 km	1.0969	45.8760	1.2410	59.7412	1.3522	72.2032	1.4366	82.7933
250 km	-	-	-	-	-	-	-	-
300 km	-	-	-	-	-	-	-	-

Appendix D
Tables for the Energy Transmission Cost of HVAC, HVDC VSC and HVDC LCC Transmission Systems for 3% interest rate

Inputs in bold indicate lowest energy transmission cost for specific transmission technology, distance and average wind speed

400 MW windfarm

€/kWh	HVAC											
	132kV				220 kV				400 kV			
	8 m/s	9m/s	10m/s	11m/s	8 m/s	9m/s	10m/s	11m/s	8 m/s	9m/s	10m/s	11m/s
50 km	0.0055	0.0048	0.0043	0.0040	0.0059	0.0051	0.0046	0.0043	0.0035	0.0030	0.0027	0.0025
100 km	0.0110	0.0096	0.0086	0.0080	0.0119	0.0103	0.0093	0.0086	**0.0070**	**0.0060**	**0.0054**	**0.0050**
150 km	0.0170	0.0148	0.0133	0.0124	0.0185	0.0160	0.0144	0.0133	**0.0107**	**0.0093**	**0.0083**	**0.0077**
200 km	**0.0236**	**0.0205**	**0.0185**	**0.0172**	0.0262	0.0226	0.0203	0.0188	0.0488	0.0419	0.0375	0.0346
250 km	**0.0449**	**0.0389**	**0.0350**	**0.0324**	0.0555	0.0476	0.0426	0.0393	-	-	-	-
300 km	**0.0583**	**0.0505**	**0.0454**	**0.0421**	-	-	-	-	-	-	-	-

Modified Case A

395 MW windfarm , Transmission Voltage: **220 kV**, Transmission Distance **50 km**				
Need for one 220 kV cable (2 needed in the non-modified version above)				
Average wind speed	8 m/s	9 m/s	10 m/s	11 m/s
Transmission Cost (€/kWh)	**0.0031**	**0.0027**	**0.0025**	**0.0023**

€/kWh	HVDC VSC											
	2x220 MW CS, 2x220 MW CP				500 MW CS, 1x500 MW CP				2x220 MW CS, 1x500 MW CP			
	8 m/s	9m/s	10m/s	11m/s	8 m/s	9m/s	10m/s	11m/s	8 m/s	9m/s	10m/s	11m/s
50 km	0.0051	0.0044	0.0040	0.0037	0.0054	0.0046	0.0042	0.0039	**0.0047**	**0.0041**	**0.0037**	**0.0035**
100 km	0.0068	0.0060	0.0054	0.0050	0.0069	0.0059	0.0053	0.0049	**0.0062**	**0.0054**	**0.0049**	**0.0045**
150 km	0.0086	0.0075	0.0068	0.0063	0.0084	0.0073	0.0065	0.0060	**0.0077**	**0.0067**	**0.0060**	**0.0056**
200 km	0.0105	0.0091	0.0082	0.0076	0.0099	0.0086	0.0077	0.0072	**0.0091**	**0.0080**	**0.0072**	**0.0067**
250 km	0.0123	0.0107	0.0097	0.0090	0.0115	0.0100	0.0090	0.0083	**0.0107**	**0.0093**	**0.0084**	**0.0078**
300 km	0.0142	0.0123	0.0112	0.0104	0.0131	0.0114	0.0102	0.0095	**0.0122**	**0.0106**	**0.0096**	**0.0089**

€/kWh	HVDC LCC											
	440 CS				500 CS				2x250 CS			
	8 m/s	9m/s	10m/s	11m/s	8 m/s	9m/s	10m/s	11m/s	8 m/s	9m/s	10m/s	11m/s
50 km	**0.0033**	**0.0029**	**0.0026**	**0.0024**	0.0038	0.0033	0.0029	0.0027	0.0040	0.0035	0.0031	0.0029
100 km	**0.0044**	**0.0038**	**0.0034**	**0.0032**	0.0050	0.0043	0.0039	0.0036	0.0054	0.0047	0.0042	0.0039
150 km	**0.0055**	**0.0048**	**0.0043**	**0.0040**	0.0062	0.0053	0.0048	0.0045	0.0069	0.0060	0.0054	0.0050
200 km	**0.0066**	**0.0057**	**0.0052**	**0.0048**	0.0074	0.0064	0.0058	0.0053	0.0083	0.0072	0.0065	0.0060
250 km	**0.0077**	**0.0067**	**0.0060**	**0.0056**	0.0086	0.0075	0.0067	0.0062	0.0098	0.0085	0.0077	0.0071
300 km	**0.0088**	**0.0077**	**0.0069**	**0.0064**	0.0098	0.0085	0.0077	0.0071	0.0113	0.0098	0.0088	0.0082

500 MW windfarm

€/kWh	HVAC											
	132kV				220 kV				400 kV			
	8 m/s	9m/s	10m/s	11m/s	8 m/s	9m/s	10m/s	11m/s	8 m/s	9m/s	10m/s	11m/s
50 km	0.0065	0.0056	0.0051	0.0047	0.0048	0.0041	0.0037	0.0035	**0.0028**	**0.0024**	**0.0022**	**0.0020**
100 km	0.0131	0.0113	0.0102	0.0095	0.0096	0.0083	0.0075	0.0070	**0.0056**	**0.0048**	**0.0044**	**0.0040**
150 km	0.0201	0.0174	0.0157	0.0146	0.0149	0.0129	0.0116	0.0108	**0.0085**	**0.0074**	**0.0066**	**0.0061**
200 km	0.0278	0.0242	0.0218	0.0202	**0.0210**	**0.0182**	**0.0163**	**0.0151**	0.0518	0.0446	0.0400	0.0369
250 km	**0.0366**	**0.0318**	**0.0287**	**0.0266**	0.0433	0.0373	0.0334	0.0309	-	-	-	-
300 km	**0.0616**	**0.0534**	**0.0480**	**0.0445**	-	-	-	-	-	-	-	-

Modified Case B

475 MW windfarm , Transmission Voltage: 132 kV, Transmission Distance 50 km				
Need for two 132 kV cable (3 needed in the non-modified version above)				
Average wind speed	8 m/s	9 m/s	10 m/s	11 m/s
Transmission Cost (€/kWh)	0.0047	0.0041	0.0037	0.0034

€/kWh	HVDC VSC											
	350+220 MW CS, 350+220 MW CP				2x350 MW CS, 2x350 MW CP				1x500 MW CS,1x500 MW CP			
	8 m/s	9m/s	10m/s	11m/s	8 m/s	9m/s	10m/s	11m/s	8 m/s	9m/s	10m/s	11m/s
50 km	0.0050	0.0044	0.0039	0.0037	0.0059	0.0051	0.0046	0.0043	**0.0043**	**0.0037**	**0.0033**	**0.0031**
100 km	0.0066	0.0058	0.0052	0.0048	0.0077	0.0067	0.0060	0.0056	**0.0055**	**0.0048**	**0.0043**	**0.0040**
150 km	0.0083	0.0072	0.0065	0.0060	0.0095	0.0083	0.0074	0.0069	**0.0067**	**0.0058**	**0.0052**	**0.0049**
200 km	0.0099	0.0087	0.0078	0.0073	0.0113	0.0098	0.0089	0.0082	**0.0080**	**0.0069**	**0.0062**	**0.0058**
250 km	0.0116	0.0101	0.0092	0.0085	0.0132	0.0115	0.0103	0.0096	**0.0092**	**0.0080**	**0.0072**	**0.0067**
300 km	0.0133	0.0116	0.0105	0.0098	0.0150	0.0131	0.0118	0.0110	**0.0105**	**0.0091**	**0.0082**	**0.0076**
€/kWh	350+220 MW CS, 1x500 MW CP				2x350 MW CS, 1x500 MW CP							
	8 m/s	9m/s	10m/s	11m/s	8 m/s	9m/s	10m/s	11m/s	8 m/s	9m/s	10m/s	11m/s
50 km	0.0046	0.0040	0.0036	0.0033	0.0053	0.0046	0.0041	0.0038				
100 km	0.0057	0.0050	0.0045	0.0042	0.0064	0.0056	0.0050	0.0047				
150 km	0.0069	0.0060	0.0054	0.0050	0.0076	0.0066	0.0060	0.0055				
200 km	0.0081	0.0071	0.0064	0.0059	0.0088	0.0076	0.0069	0.0064				
250 km	0.0093	0.0081	0.0074	0.0068	0.0100	0.0087	0.0079	0.0073				
300 km	0.0106	0.0092	0.0083	0.0077	0.0112	0.0098	0.0088	0.0082				

€/kWh	HVDC LCC											
	500 CS				2 x 250 CS				600 CS			
	8 m/s	9m/s	10m/s	11m/s	8 m/s	9m/s	10m/s	11m/s	8 m/s	9m/s	10m/s	11m/s
50 km	**0.0030**	**0.0026**	**0.0023**	**0.0022**	0.0032	0.0028	0.0025	0.0023	0.0036	0.0031	0.0028	0.0026
100 km	**0.0040**	**0.0034**	**0.0031**	**0.0029**	0.0043	0.0038	0.0034	0.0032	0.0047	0.0040	0.0036	0.0034
150 km	**0.0049**	**0.0043**	**0.0039**	**0.0036**	0.0055	0.0048	0.0043	0.0040	0.0058	0.0050	0.0045	0.0042
200 km	**0.0059**	**0.0051**	**0.0046**	**0.0043**	0.0067	0.0058	0.0053	0.0049	0.0069	0.0060	0.0054	0.0050
250 km	**0.0069**	**0.0060**	**0.0054**	**0.0050**	0.0079	0.0069	0.0062	0.0057	0.0080	0.0070	0.0063	0.0058
300 km	**0.0079**	**0.0068**	**0.0062**	**0.0057**	0.0091	0.0079	0.0071	0.0066	0.0092	0.0079	0.0072	0.0066

600 MW windfarm

€/kWh	HVAC											
	132kV				220 kV				400 kV			
	8 m/s	9m/s	10m/s	11m/s	8 m/s	9m/s	10m/s	11m/s	8 m/s	9m/s	10m/s	11m/s
50 km	0.0055	0.0047	0.0043	0.0040	0.0040	0.0035	0.0032	0.0029	**0.0024**	**0.0021**	**0.0018**	**0.0017**
100 km	0.0110	0.0096	0.0086	0.0080	0.0081	0.0070	0.0063	0.0059	**0.0047**	**0.0040**	**0.0036**	**0.0034**
150 km	0.0169	0.0147	0.0133	0.0123	0.0125	0.0109	0.0098	0.0091	**0.0071**	**0.0062**	**0.0055**	**0.0051**
200 km	**0.0236**	**0.0205**	**0.0185**	**0.0172**	0.0260	0.0225	0.0203	0.0188	0.0529	0.0458	0.0412	0.0381
250 km	**0.0400**	**0.0347**	**0.0313**	**0.0290**	0.0482	0.0415	0.0373	0.0344	-	-	-	-
300 km	**0.0636**	**0.0552**	**0.0497**	**0.0460**	-	-	-	-	-	-	-	-

€/kWh	HVDC VSC											
	2x350 MW CS, 2x350 MW CP				500+220 MW CS, 500+220 MW CP							
	8 m/s	9m/s	10m/s	11m/s	8 m/s	9m/s	10m/s	11m/s	8 m/s	9m/s	10m/s	11m/s
50 km	0.0050	0.0043	0.0039	0.0036	**0.0049**	**0.0042**	**0.0038**	**0.0036**				
100 km	0.0065	0.0057	0.0051	0.0047	**0.0062**	**0.0054**	**0.0049**	**0.0045**				
150 km	0.0080	0.0070	0.0063	0.0059	**0.0075**	**0.0065**	**0.0059**	**0.0055**				
200 km	0.0096	0.0084	0.0076	0.0070	**0.0088**	**0.0077**	**0.0070**	**0.0065**				
250 km	0.0112	0.0097	0.0088	0.0082	**0.0102**	**0.0089**	**0.0080**	**0.0075**				
300 km	0.0128	0.0111	0.0101	0.0094	**0.0116**	**0.0101**	**0.0091**	**0.0085**				

€/kWh	HVDC LCC											
	600 CS				440 CS + 250 CS				2 x 300 CS			
	8 m/s	9m/s	10m/s	11m/s	8 m/s	9m/s	10m/s	11m/s	8 m/s	9m/s	10m/s	11m/s
50 km	**0.0030**	**0.0026**	**0.0023**	**0.0021**	0.0035	0.0031	0.0028	0.0026	0.0031	0.0027	0.0024	0.0023
100 km	**0.0039**	**0.0034**	**0.0030**	**0.0028**	0.0047	0.0041	0.0037	0.0034	0.0042	0.0036	0.0033	0.0031
150 km	**0.0048**	**0.0042**	**0.0038**	**0.0035**	0.0059	0.0051	0.0046	0.0043	0.0053	0.0046	0.0042	0.0039
200 km	**0.0057**	**0.0050**	**0.0045**	**0.0042**	0.0071	0.0062	0.0056	0.0052	0.0064	0.0056	0.0050	0.0047
250 km	**0.0067**	**0.0058**	**0.0052**	**0.0048**	0.0083	0.0073	0.0065	0.0061	0.0075	0.0065	0.0059	0.0055
300 km	**0.0076**	**0.0066**	**0.0060**	**0.0055**	0.0096	0.0083	0.0075	0.0070	0.0086	0.0075	0.0068	0.0063

700 MW windfarm

€/kWh	HVAC											
	132kV				220 kV				400 kV			
	8 m/s	9m/s	10m/s	11m/s	8 m/s	9m/s	10m/s	11m/s	8 m/s	9m/s	10m/s	11m/s
50 km	0.0047	0.0041	0.0037	0.0034	0.0035	0.0030	0.0027	0.0025	**0.0020**	**0.0018**	**0.0016**	**0.0015**
100 km	0.0125	0.0109	0.0098	0.0091	0.0070	0.0061	0.0055	0.0051	**0.0040**	**0.0035**	**0.0031**	**0.0029**
150 km	0.0191	0.0166	0.0150	0.0139	0.0160	0.0139	0.0125	0.0115	0.0119	0.0104	0.0093	0.0086
200 km	0.0264	0.0230	0.0207	0.0192	**0.0224**	**0.0194**	**0.0174**	**0.0161**	0.0453	0.0391	0.0351	0.0324
250 km	**0.0348**	**0.0303**	**0.0274**	**0.0254**	0.0408	0.0352	0.0316	0.0292	-	-	-	-
300 km	**0.0550**	**0.0478**	**0.0431**	**0.0400**	-	-	-	-	-	-	-	-

Modified Case C

680 MW windfarm , Transmission Voltage: 220 kV, Transmission Distance 150 km				
Need for two 220 kV cable (3 needed in the non-modified version above)				
Average wind speed	8 m/s	9 m/s	10 m/s	11 m/s
Transmission Cost (€/kWh)	**0.0112**	**0.0097**	**0.0088**	**0.0081**

€/kWh	HVDC VSC											
	2x350 MW CS, 2x350 MW CP				500+220 MW CS, 500+220 MW CP							
	8 m/s	9m/s	10m/s	11m/s	8 m/s	9m/s	10m/s	11m/s	8 m/s	9m/s	10m/s	11m/s
50 km	0.0043	0.0038	0.0034	0.0032	**0.0042**	**0.0037**	**0.0033**	**0.0031**				
100 km	0.0056	0.0049	0.0044	0.0041	**0.0054**	**0.0047**	**0.0042**	**0.0039**				
150 km	0.0070	0.0061	0.0055	0.0051	**0.0065**	**0.0057**	**0.0051**	**0.0048**				
200 km	0.0083	0.0073	0.0066	0.0061	**0.0077**	**0.0067**	**0.0061**	**0.0056**				
250 km	0.0097	0.0085	0.0077	0.0072	**0.0089**	**0.0078**	**0.0070**	**0.0065**				
300 km	0.0111	0.0097	0.0088	0.0082	**0.0101**	**0.0088**	**0.0080**	**0.0074**				

€/kWh	HVDC LCC											
	500 CS + 250 CS				440 CS + 300 CS				3 x 250 CS			
	8 m/s	9m/s	10m/s	11m/s	8 m/s	9m/s	10m/s	11m/s	8 m/s	9m/s	10m/s	11m/s
50 km	0.0033	0.0028	0.0026	0.0024	0.0032	0.0028	0.0025	0.0023	0.0034	0.0030	0.0027	0.0025
100 km	0.0044	0.0038	0.0034	0.0032	0.0043	0.0037	0.0034	0.0031	0.0046	0.0040	0.0036	0.0034
150 km	0.0055	0.0047	0.0043	0.0040	0.0054	0.0047	0.0042	0.0039	0.0059	0.0051	0.0046	0.0043
200 km	0.0066	0.0057	0.0051	0.0048	0.0065	0.0056	0.0051	0.0047	0.0071	0.0062	0.0056	0.0052
250 km	0.0077	0.0067	0.0060	0.0056	0.0076	0.0066	0.0059	0.0055	0.0084	0.0073	0.0066	0.0061
300 km	0.0088	0.0077	0.0069	0.0064	0.0087	0.0076	0.0068	0.0063	0.0097	0.0084	0.0076	0.0071
€/kWh	600 CS + 130 CS											
	8 m/s	9m/s	10m/s	11m/s	8 m/s	9m/s	10m/s	11m/s	8 m/s	9m/s	10m/s	11m/s
50 km	**0.0032**	**0.0028**	**0.0025**	**0.0023**								
100 km	**0.0042**	**0.0037**	**0.0033**	**0.0031**								
150 km	**0.0053**	**0.0046**	**0.0042**	**0.0039**								
200 km	**0.0064**	**0.0056**	**0.0050**	**0.0047**								
250 km	**0.0075**	**0.0065**	**0.0059**	**0.0055**								
300 km	**0.0086**	**0.0075**	**0.0067**	**0.0063**								

800 MW windfarm

€/kWh	HVAC											
	132kV				220 kV				400 kV			
	8 m/s	9m/s	10m/s	11m/s	8 m/s	9m/s	10m/s	11m/s	8 m/s	9m/s	10m/s	11m/s
50 km	0.0054	0.0047	0.0043	0.0040	0.0045	0.0039	0.0035	0.0033	**0.0018**	**0.0016**	**0.0014**	**0.0013**
100 km	0.0110	0.0095	0.0086	0.0080	0.0090	0.0079	0.0071	0.0066	0.0069	0.0060	0.0054	0.0050
150 km	0.0169	0.0147	0.0133	0.0123	0.0140	0.0121	0.0109	0.0101	**0.0105**	**0.0091**	**0.0082**	**0.0076**
200 km	0.0234	0.0204	0.0185	0.0171	**0.0196**	**0.0170**	**0.0154**	**0.0142**	0.0472	0.0408	0.0367	0.0340
250 km	0.0376	0.0327	0.0295	0.0274	**0.0356**	**0.0308**	**0.0277**	**0.0256**	-	-	-	-
300 km	**0.0573**	**0.0498**	**0.0450**	**0.0417**	-	-	-	-	-	-	-	-

Modified Cases D, E

790 MW windfarm , Transmission Voltage: 220 kV, Transmission Distance **50 km**				
Need for two 220 kV cable (3 needed in the non-modified version above)				
Average wind speed	8 m/s	9 m/s	10 m/s	11 m/s
Transmission Cost (€/kWh)	0.0031	0.0027	0.0025	0.0023
795 MW windfarm , Transmission Voltage: 400 kV, Transmission Distance **100 km**				
Need for one 400 kV cable (2 needed in the non-modified version above)				
Average wind speed	8 m/s	9 m/s	10 m/s	11 m/s
Transmission Cost (€/kWh)	**0.0035**	**0.0031**	**0.0028**	**0.0026**

€/kWh	HVDC VSC											
	2x350+220 MW CS,2x 350+220 MW CP				3x350 MW CS, 3x350 MW CP				500+350 MW CS, 500+350 MW CP			
	8 m/s	9m/s	10m/s	11m/s	8 m/s	9m/s	10m/s	11m/s	8 m/s	9m/s	10m/s	11m/s
50 km	0.0049	0.0043	0.0039	0.0036	0.0054	0.0047	0.0043	0.0040	**0.0045**	**0.0039**	**0.0035**	**0.0033**
100 km	0.0065	0.0056	0.0051	0.0047	0.0071	0.0062	0.0056	0.0052	**0.0057**	**0.0050**	**0.0045**	**0.0042**
150 km	0.0080	0.0070	0.0063	0.0059	0.0087	0.0076	0.0069	0.0064	**0.0071**	**0.0062**	**0.0056**	**0.0052**
200 km	0.0096	0.0084	0.0076	0.0071	0.0104	0.0091	0.0082	0.0076	**0.0084**	**0.0073**	**0.0066**	**0.0062**
250 km	0.0112	0.0098	0.0089	0.0083	0.0121	0.0106	0.0095	0.0088	**0.0097**	**0.0085**	**0.0077**	**0.0072**
300 km	0.0129	0.0112	0.0102	0.0095	0.0138	0.0121	0.0109	0.0101	**0.0111**	**0.0097**	**0.0088**	**0.0082**

€/kWh	HVDC LCC											
	500 CS + 300 CS				2 x 440 CS				600 CS + 250 CS			
	8 m/s	9m/s	10m/s	11m/s	8 m/s	9m/s	10m/s	11m/s	8 m/s	9m/s	10m/s	11m/s
50 km	**0.0030**	**0.0026**	**0.0024**	**0.0022**	0.0033	0.0029	0.0026	0.0024	0.0032	0.0028	0.0025	0.0023
100 km	**0.0040**	**0.0035**	**0.0032**	**0.0029**	0.0044	0.0038	0.0034	0.0032	0.0042	0.0037	0.0033	0.0031
150 km	**0.0050**	**0.0044**	**0.0040**	**0.0037**	0.0055	0.0047	0.0043	0.0040	0.0053	0.0046	0.0042	0.0038
200 km	**0.0061**	**0.0053**	**0.0048**	**0.0044**	0.0065	0.0057	0.0051	0.0048	0.0063	0.0055	0.0050	0.0046
250 km	**0.0071**	**0.0062**	**0.0056**	**0.0052**	0.0076	0.0066	0.0060	0.0055	0.0074	0.0064	0.0058	0.0054
300 km	**0.0081**	**0.0071**	**0.0064**	**0.0059**	0.0087	0.0076	0.0069	0.0064	0.0085	0.0074	0.0067	0.0062

900 MW windfarm

€/kWh	HVAC											
	132kV				220 kV				400 kV			
	8 m/s	9m/s	10m/s	11m/s	8 m/s	9m/s	10m/s	11m/s	8 m/s	9m/s	10m/s	11m/s
50 km	0.0049	0.0042	0.0038	0.0036	0.0040	0.0035	0.0032	0.0029	0.0031	0.0027	0.0024	0.0022
100 km	0.0098	0.0086	0.0077	0.0072	0.0081	0.0070	0.0063	0.0059	**0.0061**	**0.0053**	**0.0048**	**0.0044**
150 km	0.0187	0.0162	0.0146	0.0136	0.0125	0.0109	0.0098	0.0091	**0.0093**	**0.0081**	**0.0073**	**0.0067**
200 km	0.0257	0.0224	0.0202	0.0188	**0.0231**	**0.0200**	**0.0180**	**0.0167**	0.0486	0.0421	0.0379	0.0351
250 km	0.0398	0.0346	0.0312	0.0290	**0.0394**	**0.0341**	**0.0306**	**0.0283**	-	-	-	-
300 km	**0.0592**	**0.0514**	**0.0463**	**0.0430**	-	-	-	-	-	-	-	-

Modified Cases F

885 MW windfarm , Transmission Voltage: 400 kV, Transmission Distance 50 km				
Need for one 400 kV cable (2 needed in the non-modified version above)				
Average wind speed	8 m/s	9 m/s	10 m/s	11 m/s
Transmission Cost (€/kWh)	**0.0016**	**0.0014**	**0.0013**	**0.0012**

€/kWh	HVDC VSC											
	3x350 MW CS, 3x350 MW CP				2x500 MW CS, 2x500 MW CP				2x350+220 MW CS,2x 350+220 MW CP			
	8 m/s	9m/s	10m/s	11m/s	8 m/s	9m/s	10m/s	11m/s	8 m/s	9m/s	10m/s	11m/s
50 km	0.0049	0.0043	0.0039	0.0036	0.0046	0.0040	0.0036	0.0033	**0.0044**	**0.0039**	**0.0035**	**0.0033**
100 km	0.0064	0.0056	0.0050	0.0047	**0.0058**	**0.0051**	**0.0046**	**0.0043**	**0.0058**	**0.0051**	**0.0046**	**0.0043**
150 km	0.0079	0.0069	0.0062	0.0058	**0.0071**	**0.0062**	**0.0056**	**0.0052**	0.0073	0.0063	0.0057	0.0053
200 km	0.0094	0.0082	0.0074	0.0069	**0.0084**	**0.0074**	**0.0067**	**0.0062**	0.0087	0.0076	0.0069	0.0064
250 km	0.0109	0.0096	0.0087	0.0080	**0.0098**	**0.0085**	**0.0077**	**0.0072**	0.0102	0.0089	0.0081	0.0075
300 km	0.0125	0.0109	0.0099	0.0092	**0.0111**	**0.0097**	**0.0088**	**0.0082**	0.0117	0.0102	0.0093	0.0086

€/kWh	HVDC LCC											
	3 x 300 CS				600 CS + 300 CS				500 CS + 440 CS			
	8 m/s	9m/s	10m/s	11m/s	8 m/s	9m/s	10m/s	11m/s	8 m/s	9m/s	10m/s	11m/s
50 km	0.0031	0.0027	0.0024	0.0023	**0.0030**	**0.0026**	**0.0024**	**0.0022**	0.0031	0.0027	0.0025	0.0023
100 km	0.0042	0.0036	0.0033	0.0031	**0.0040**	**0.0035**	**0.0031**	**0.0029**	0.0041	0.0036	0.0032	0.0030
150 km	0.0053	0.0046	0.0042	0.0038	**0.0049**	**0.0043**	**0.0039**	**0.0036**	0.0051	0.0045	0.0040	0.0037
200 km	0.0064	0.0056	0.0050	0.0047	**0.0059**	**0.0052**	**0.0047**	**0.0043**	0.0062	0.0054	0.0048	0.0045
250 km	0.0075	0.0065	0.0059	0.0055	**0.0069**	**0.0060**	**0.0054**	**0.0050**	0.0072	0.0062	0.0056	0.0052
300 km	0.0086	0.0075	0.0068	0.0063	**0.0079**	**0.0069**	**0.0062**	**0.0058**	0.0082	0.0071	0.0064	0.0060

1000 MW windfarm

€/kWh	HVAC											
	132kV				220 kV				400 kV			
	8 m/s	9m/s	10m/s	11m/s	8 m/s	9m/s	10m/s	11m/s	8 m/s	9m/s	10m/s	11m/s
50 km	0.0054	0.0047	0.0043	0.0040	0.0037	0.0032	0.0029	0.0027	**0.0028**	**0.0024**	**0.0022**	**0.0020**
100 km	0.0110	0.0095	0.0086	0.0080	0.0073	0.0064	0.0058	0.0053	**0.0055**	**0.0048**	**0.0043**	**0.0040**
150 km	0.0169	0.0147	0.0133	0.0123	0.0114	0.0099	0.0089	0.0083	**0.0084**	**0.0073**	**0.0066**	**0.0061**
200 km	0.0234	0.0204	0.0185	0.0171	**0.0208**	**0.0181**	**0.0163**	**0.0151**	0.0437	0.0379	0.0341	0.0315
250 km	**0.0362**	**0.0315**	**0.0285**	**0.0264**	0.0425	0.0368	0.0331	0.0306	-	-	-	-
300 km	**0.0606**	**0.0527**	**0.0475**	**0.0440**	-	-	-	-	-	-	-	-

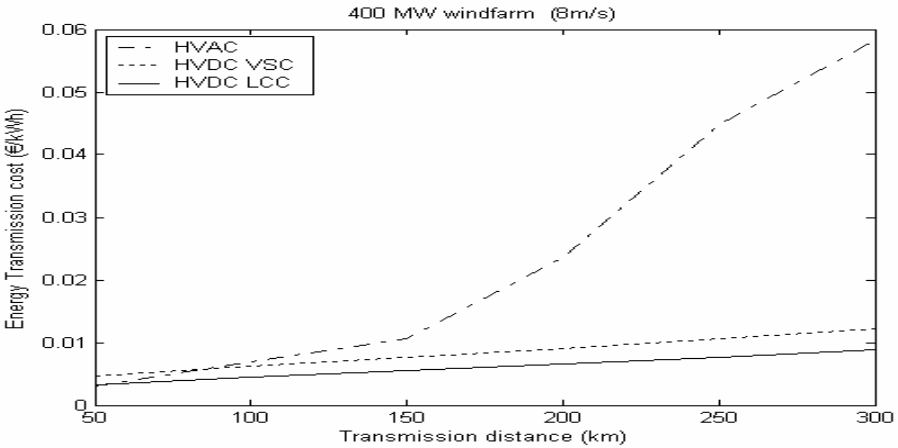
€/kWh	HVDC VSC											
	3x350 MW CS, 3x350 MW CP				2x500 MW CS, 2x500 MW CP							
	8 m/s	9m/s	10m/s	11m/s	8 m/s	9m/s	10m/s	11m/s	8 m/s	9m/s	10m/s	11m/s
50 km	0.0045	0.0039	0.0035	0.0033	**0.0041**	**0.0036**	**0.0033**	**0.0030**				
100 km	0.0058	0.0051	0.0046	0.0043	**0.0053**	**0.0046**	**0.0042**	**0.0039**				
150 km	0.0072	0.0063	0.0057	0.0053	**0.0065**	**0.0057**	**0.0051**	**0.0048**				
200 km	0.0086	0.0075	0.0068	0.0063	**0.0077**	**0.0067**	**0.0061**	**0.0056**				
250 km	0.0100	0.0088	0.0080	0.0074	**0.0089**	**0.0078**	**0.0070**	**0.0066**				
300 km	0.0115	0.0100	0.0091	0.0085	**0.0101**	**0.0089**	**0.0080**	**0.0075**				

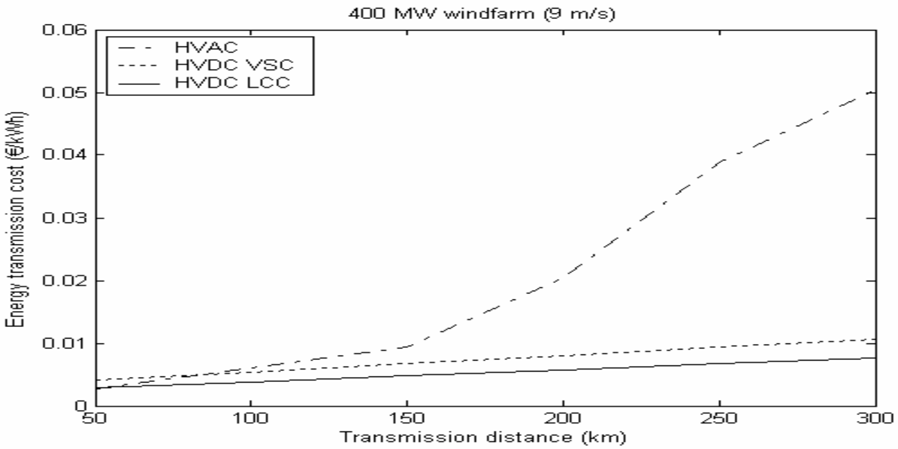
€/kWh	HVDC LCC											
	2 x 500 CS				600 CS + 440 CS				500 CS + 600 CS			
	8 m/s	9m/s	10m/s	11m/s	8 m/s	9m/s	10m/s	11m/s	8 m/s	9m/s	10m/s	11m/s
50 km	**0.0030**	**0.0026**	**0.0023**	**0.0022**	0.0031	0.0027	0.0024	0.0022	0.0033	0.0028	0.0026	0.0024
100 km	**0.0039**	**0.0034**	**0.0031**	**0.0029**	0.0041	0.0035	0.0032	0.0030	0.0043	0.0037	0.0034	0.0031
150 km	**0.0049**	**0.0043**	**0.0038**	**0.0036**	0.0050	0.0044	0.0040	0.0037	0.0053	0.0046	0.0042	0.0039
200 km	**0.0059**	**0.0051**	**0.0046**	**0.0043**	0.0060	0.0052	0.0047	0.0044	0.0063	0.0055	0.0050	0.0046
250 km	**0.0068**	**0.0059**	**0.0054**	**0.0050**	0.0070	0.0061	0.0055	0.0051	0.0074	0.0064	0.0058	0.0054
300 km	**0.0078**	**0.0068**	**0.0061**	**0.0057**	0.0080	0.0070	0.0063	0.0058	0.0084	0.0073	0.0066	0.0061
€/kWh	2 x 600 CS											
	8 m/s	9m/s	10m/s	11m/s	8 m/s	9m/s	10m/s	11m/s	8 m/s	9m/s	10m/s	11m/s
50 km	0.0035	0.0031	0.0028	0.0026								
100 km	0.0046	0.0040	0.0036	0.0034								
150 km	0.0057	0.0050	0.0045	0.0042								
200 km	0.0068	0.0059	0.0053	0.0050								
250 km	0.0079	0.0069	0.0062	0.0058								
300 km	0.0090	0.0079	0.0071	0.0066								

Appendix E
Graphical comparison of energy transmission cost for systems with the best performance from each technology. Interest rate at 3%

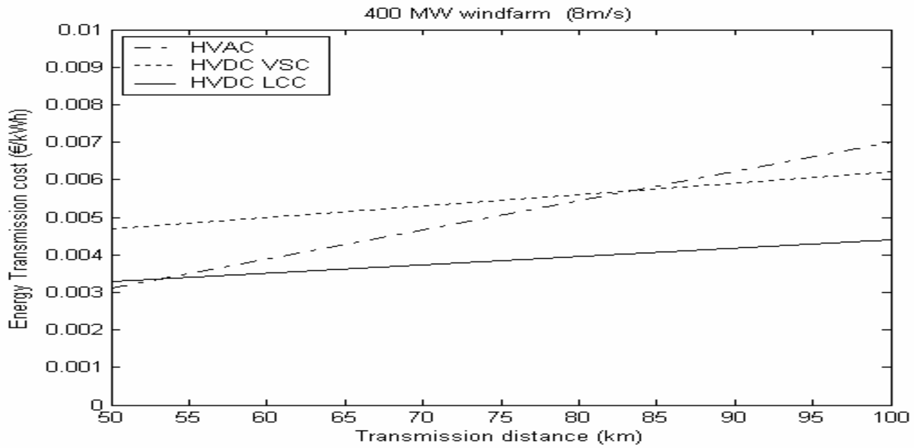
400 MW windfarm
8 and 9 m/sec average wind speed

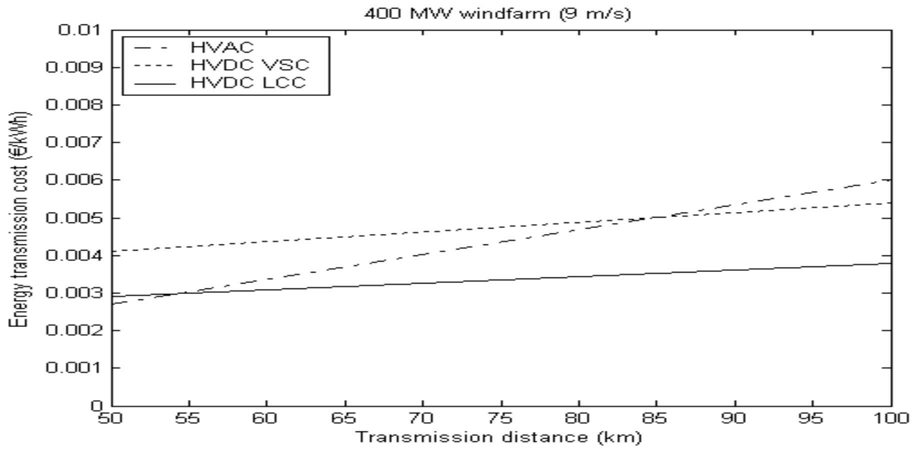
50 – 300 km transmission length



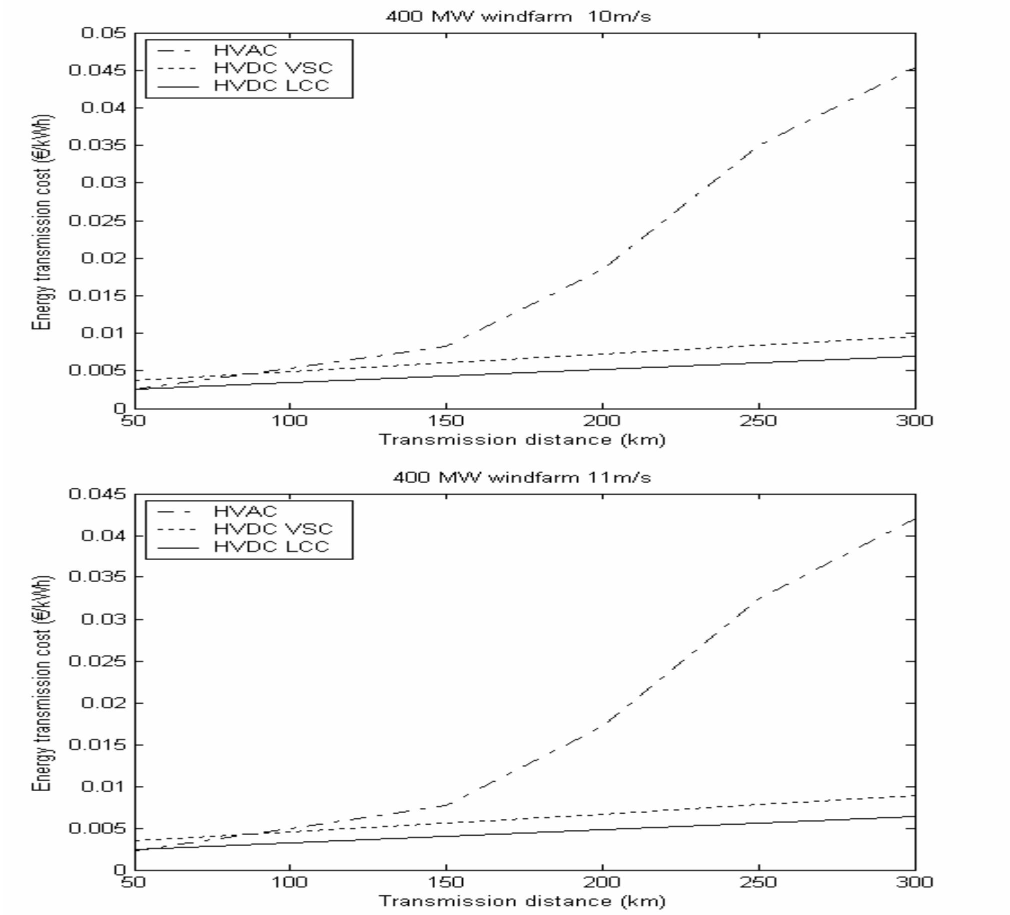


Detailed area

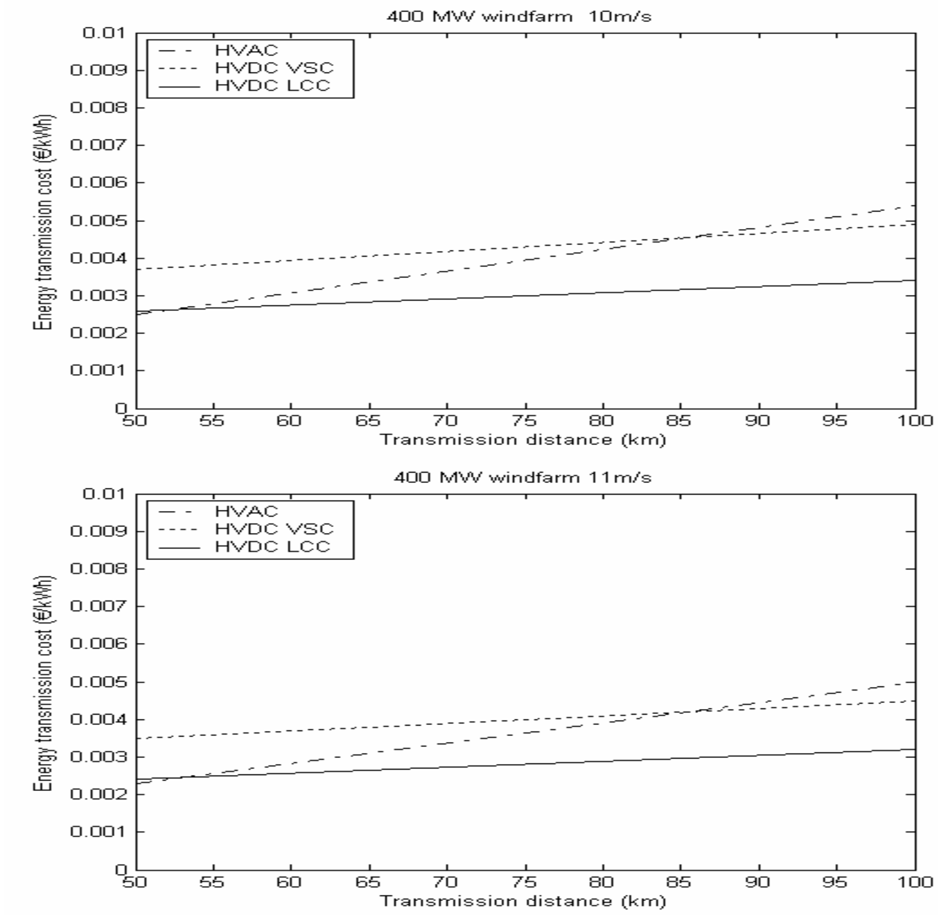




400 MW windfarm
10 and 11 m/sec average wind speed
50 – 300 km transmission length

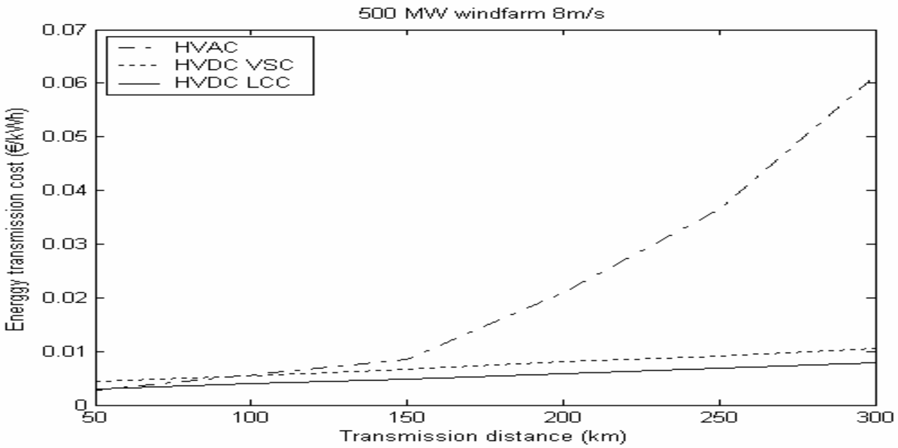


Detailed area

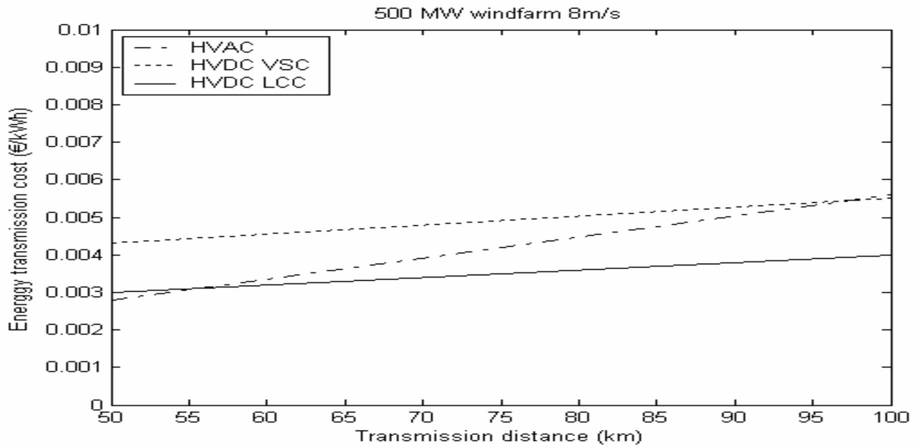


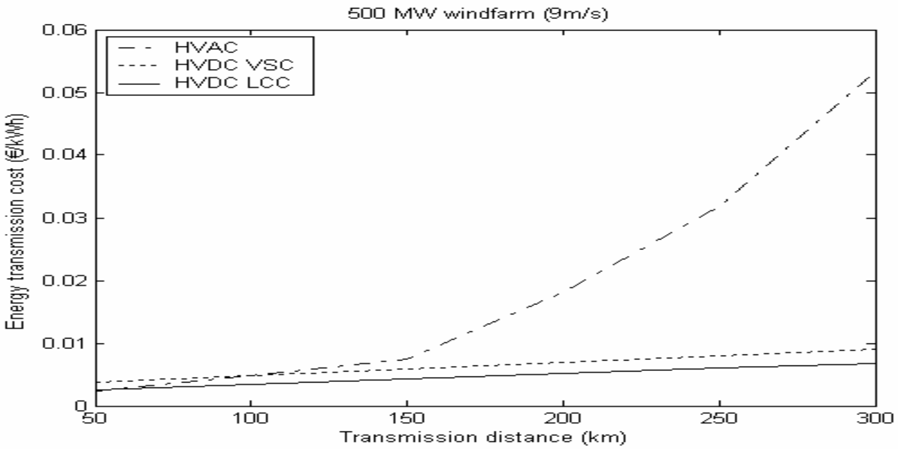
500 MW windfarm
8 and 9 m/sec average wind speed

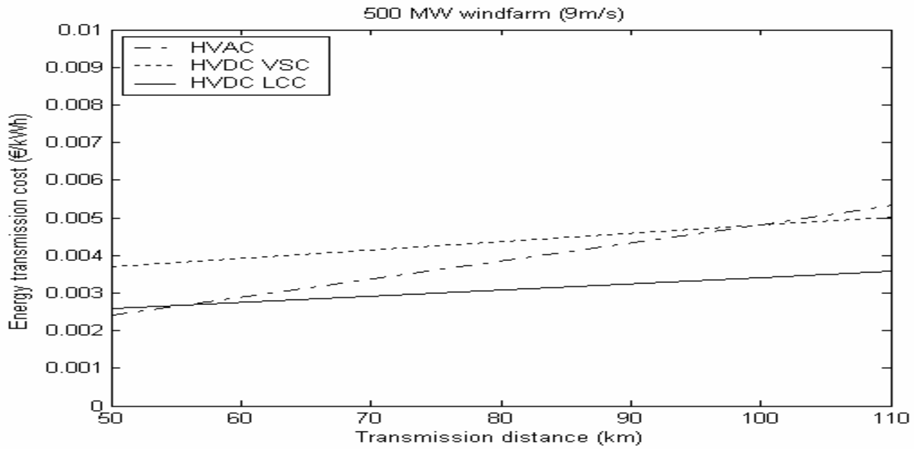
50 – 300 km transmission length



Detailed area

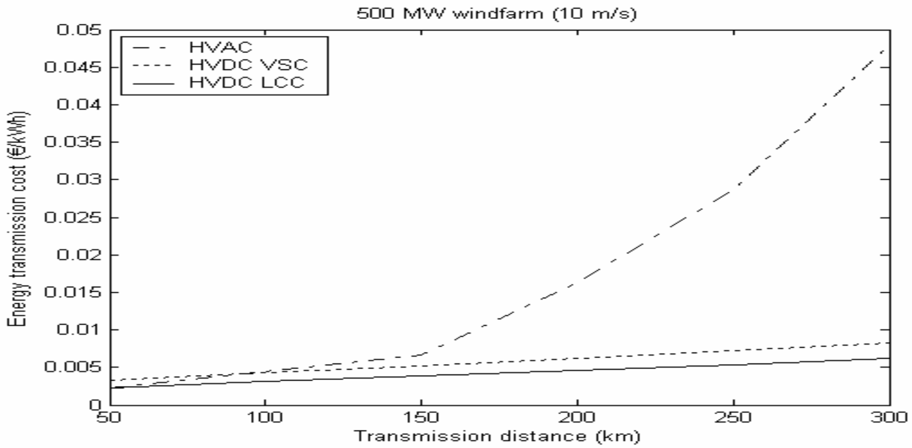


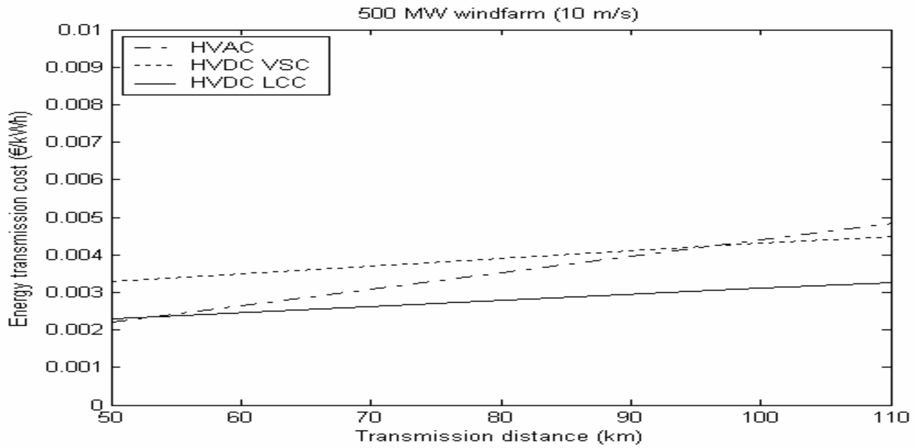


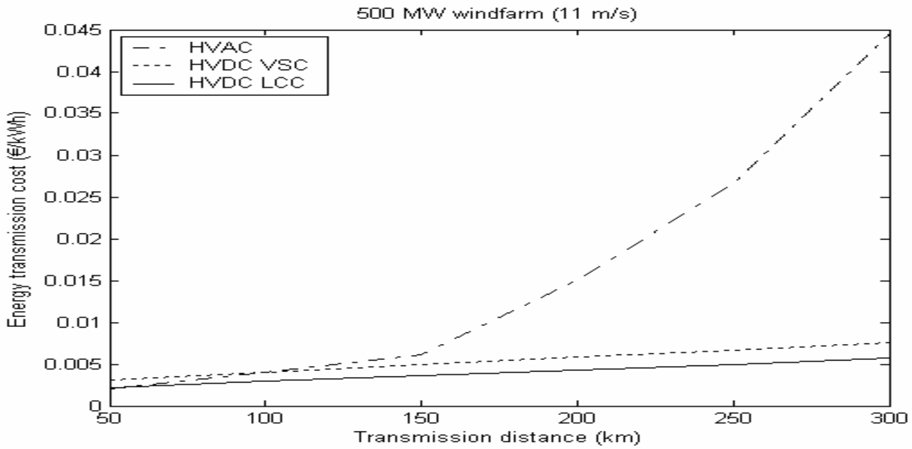


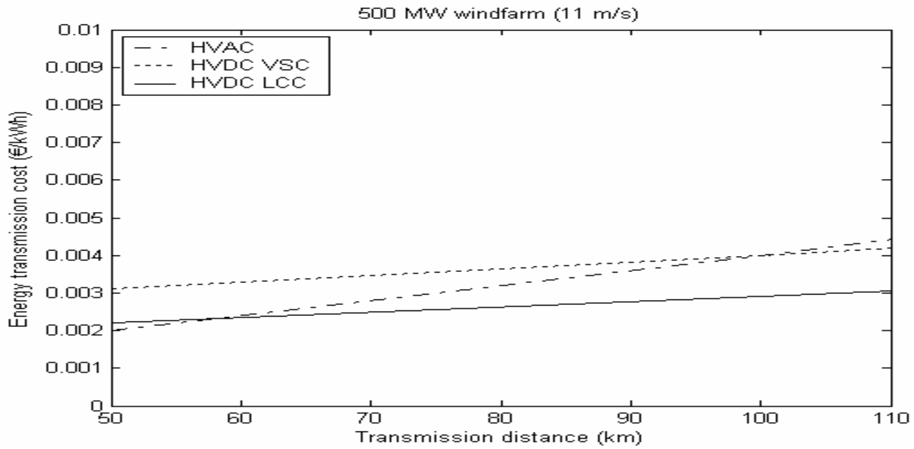
500 MW windfarm
10 and 11 m/sec average wind speed
50 – 300 km transmission length

Detailed area







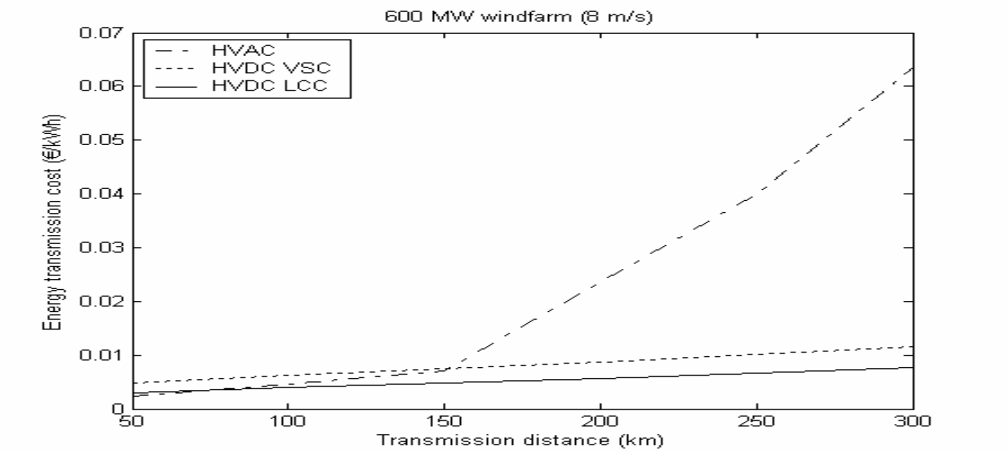


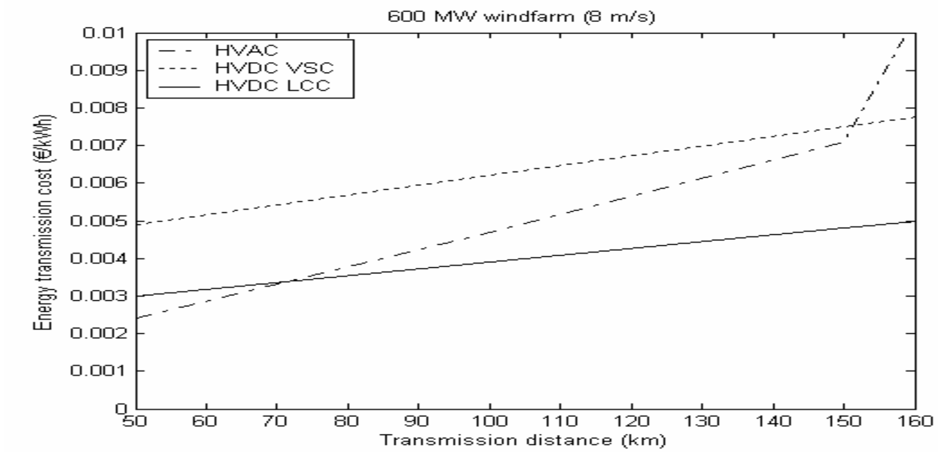
600 MW windfarm

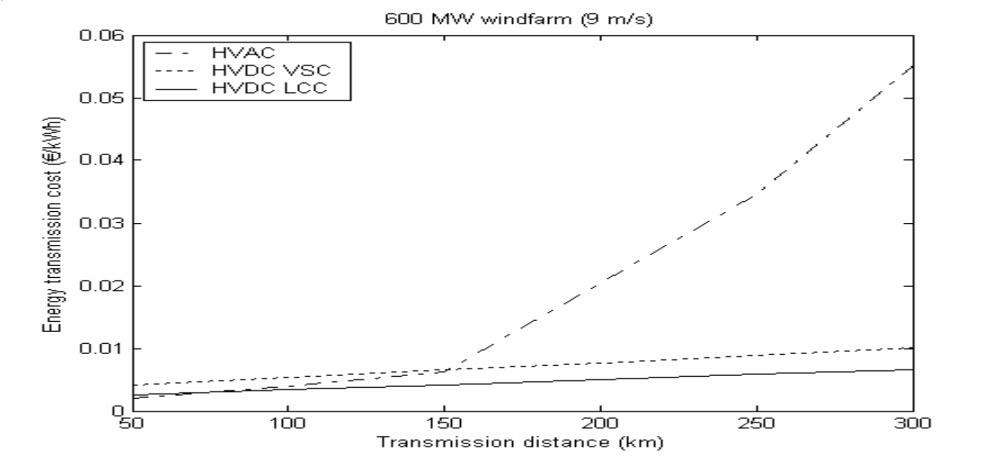
8 and 9 m/sec average wind speed

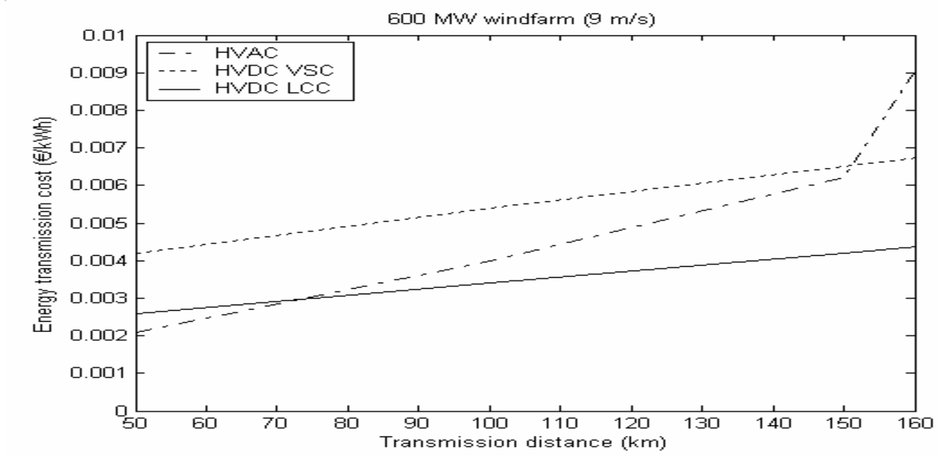
50 – 300 km transmission length

Detailed area





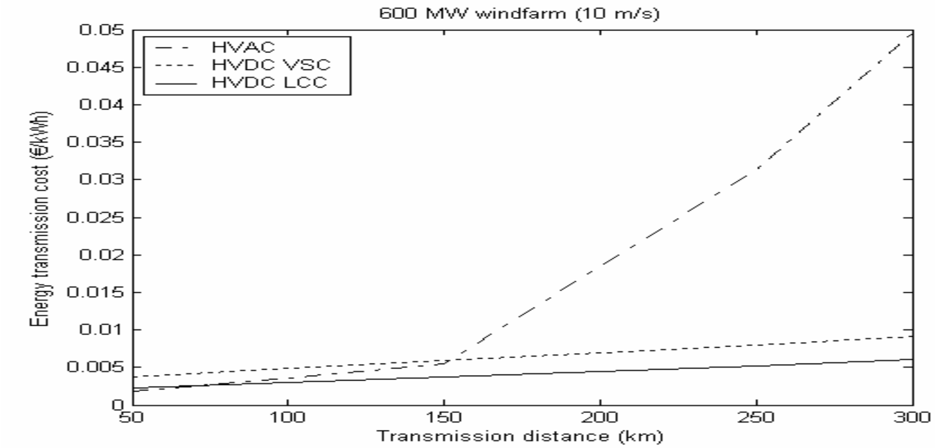


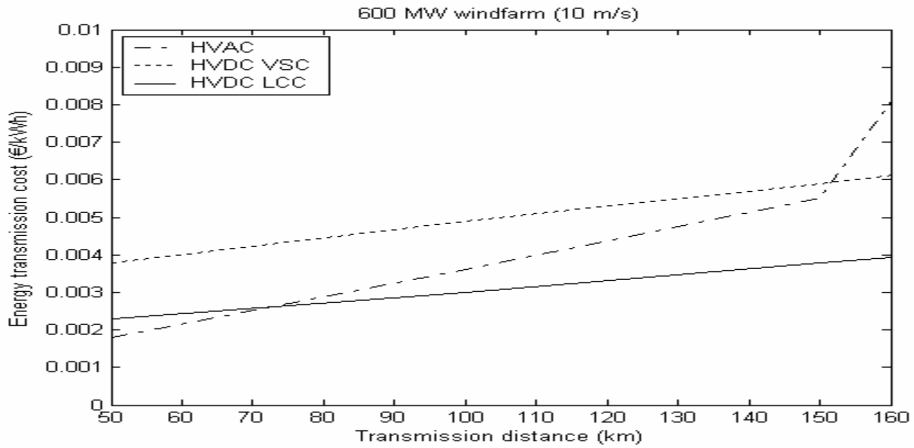


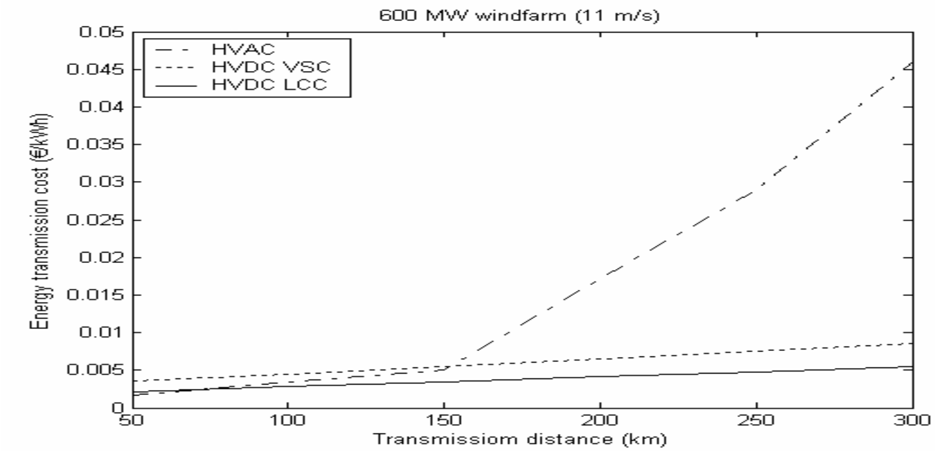
600 MW windfarm
10 and 11 m/sec average wind speed

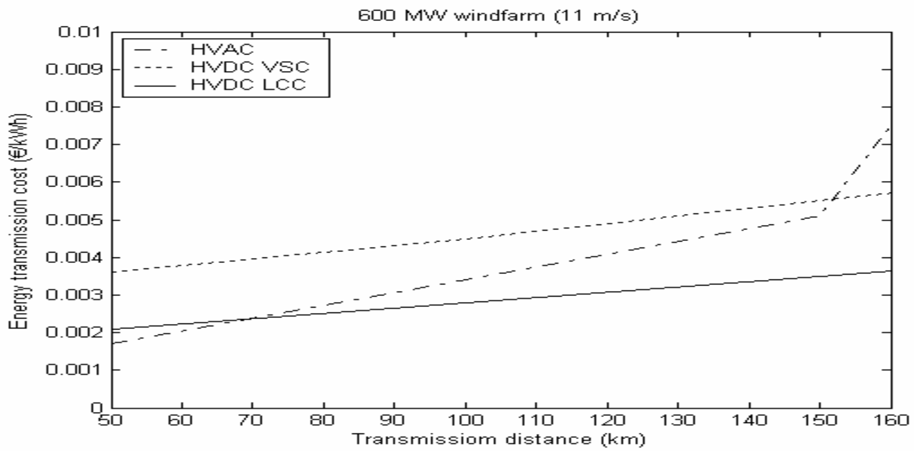
50 – 300 km transmission length

Detailed area





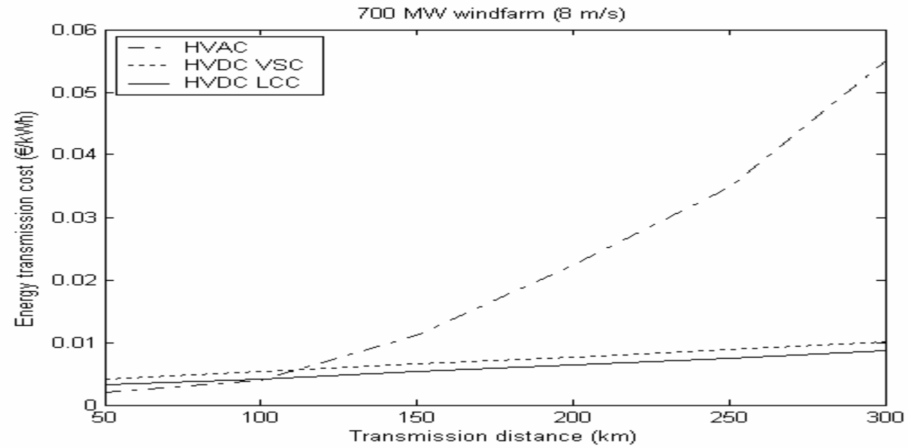


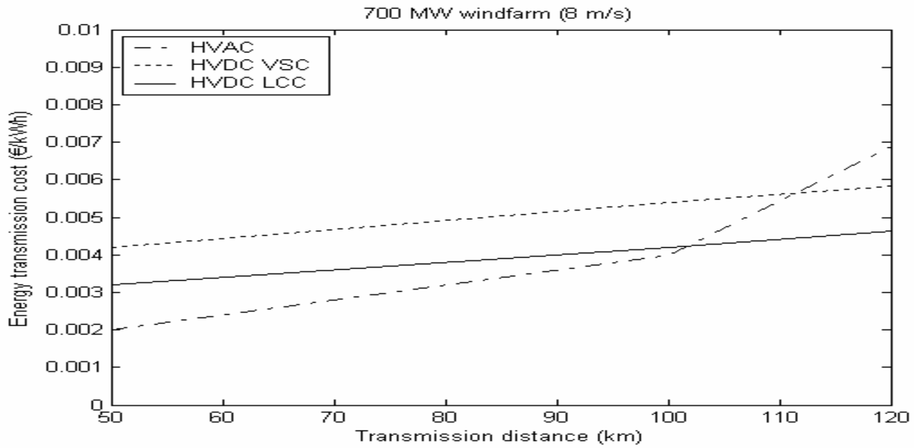


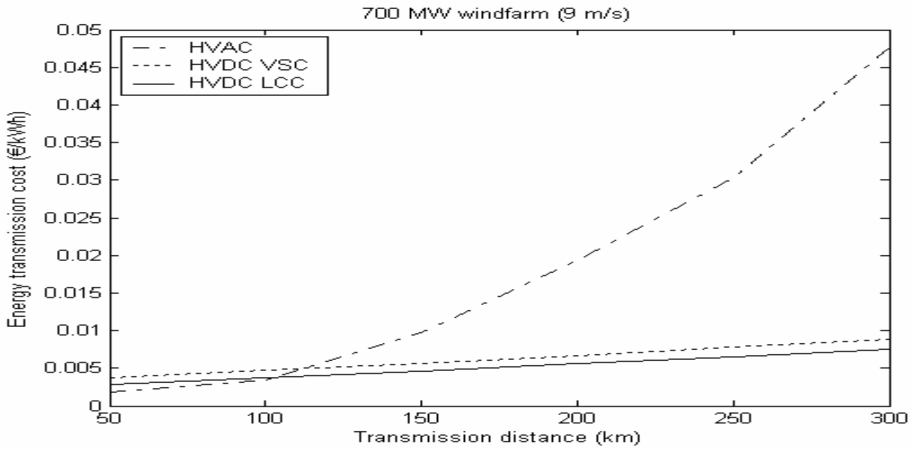
700 MW windfarm
8 and 9 m/sec average wind speed

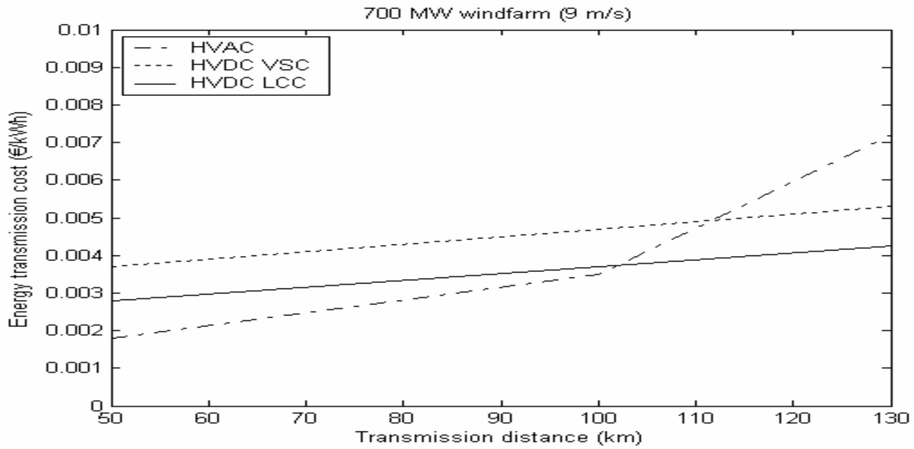
50 – 300 km transmission length

Detailed area





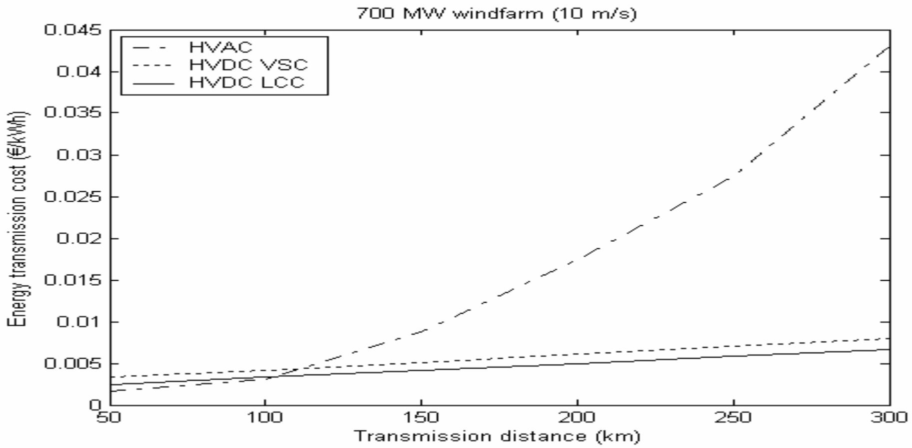


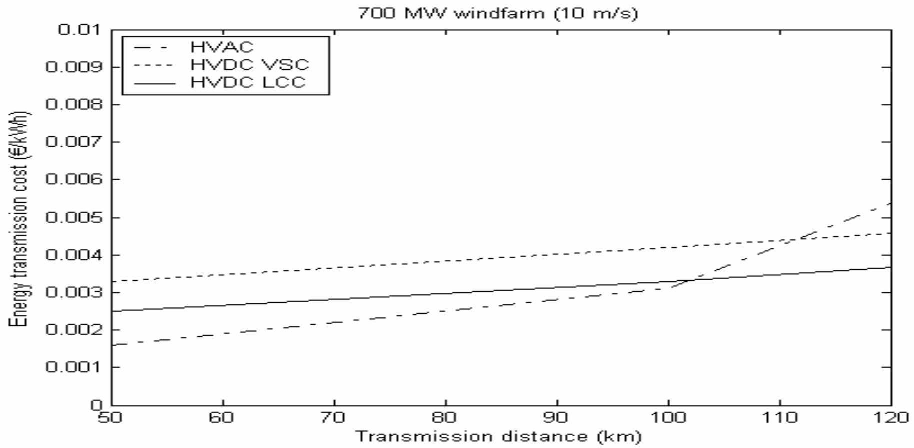


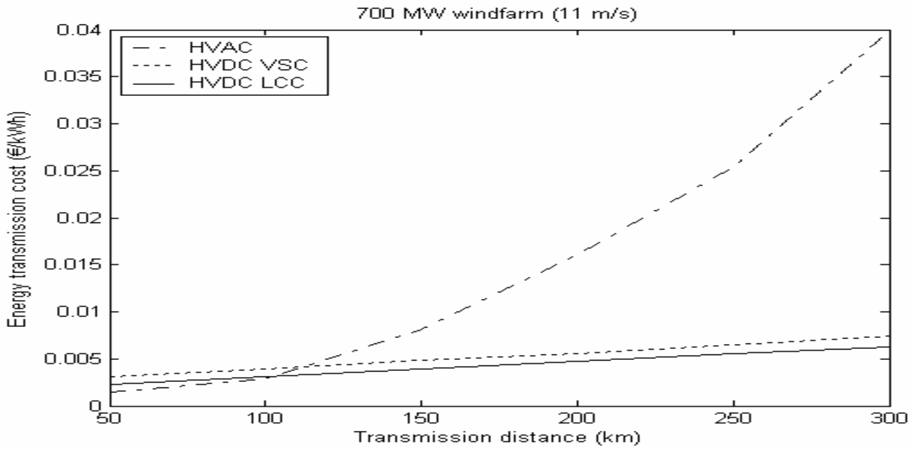
700 MW windfarm
10 and 11 m/sec average wind speed

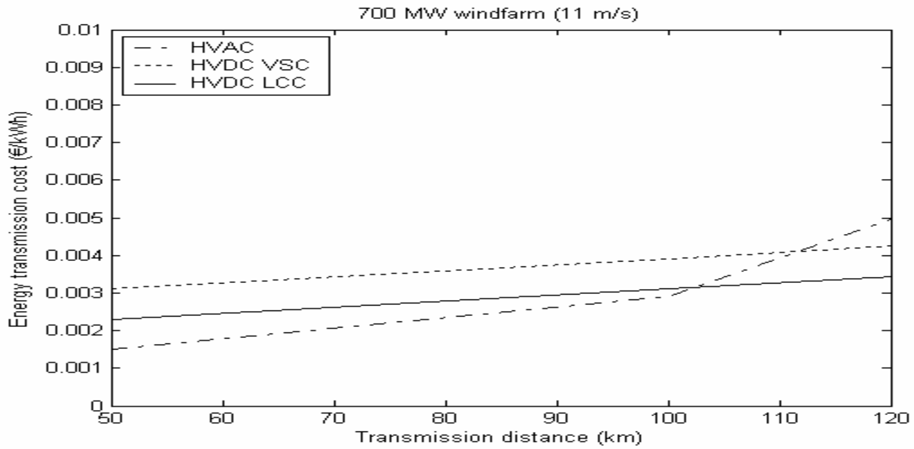
50 – 300 km transmission length

Detailed area





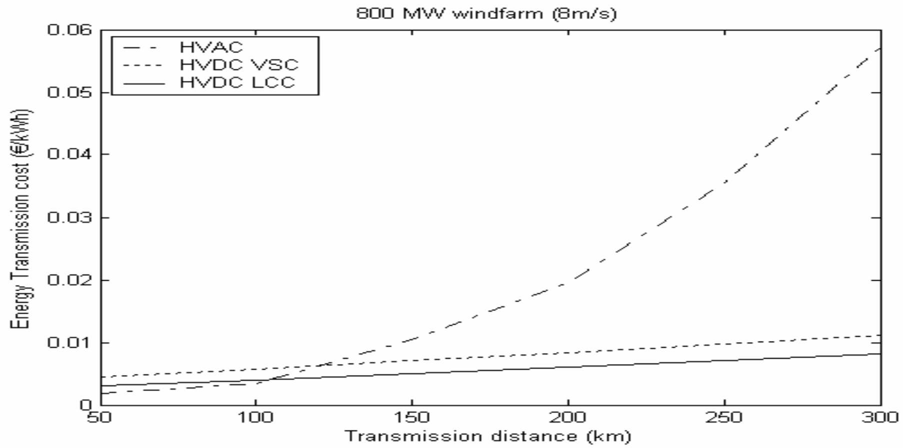


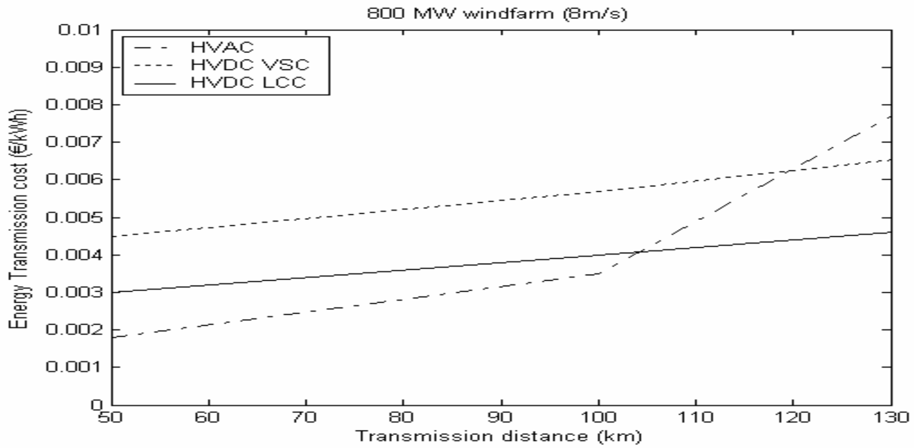


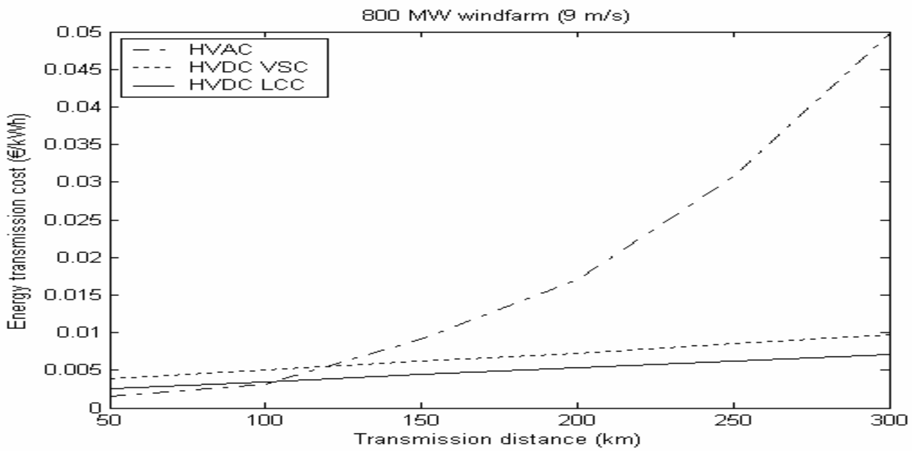
800 MW windfarm
8 and 9 m/sec average wind speed

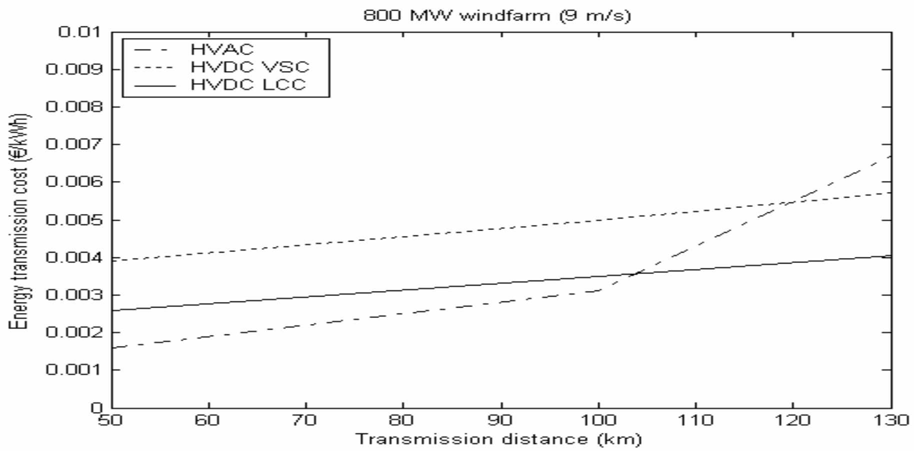
50 – 300 km transmission length

Detailed area





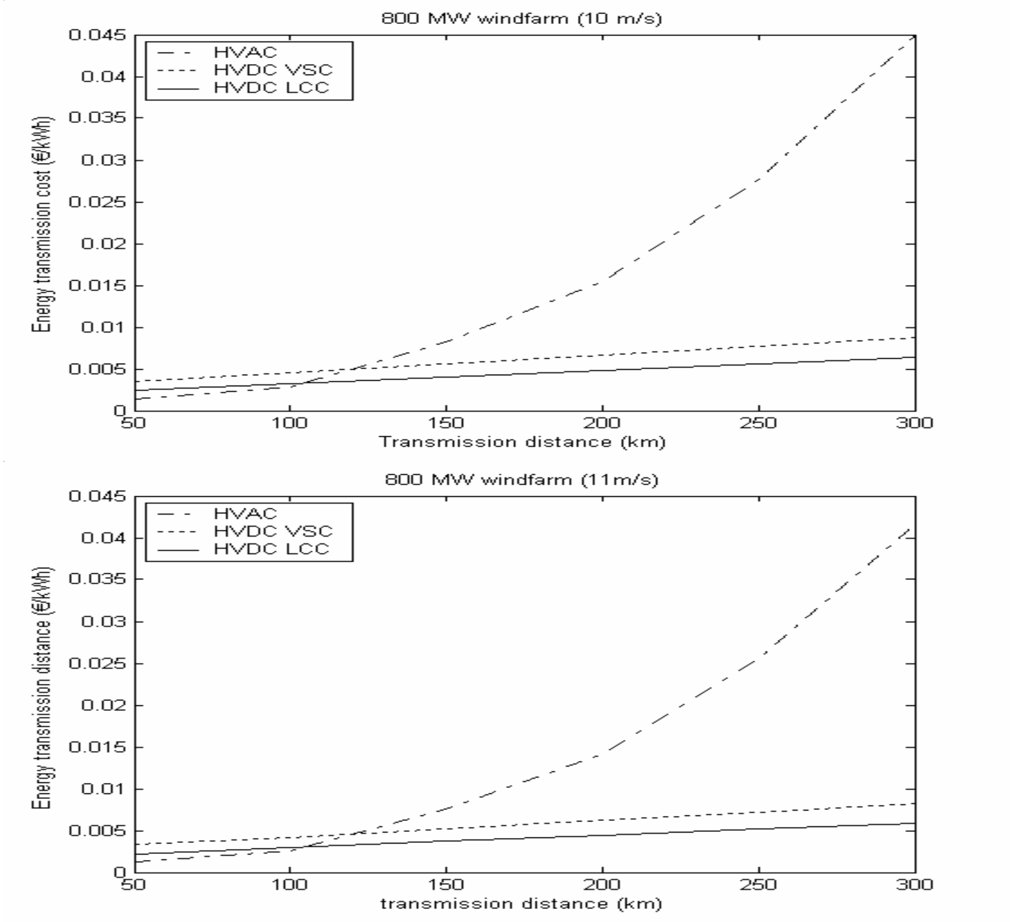




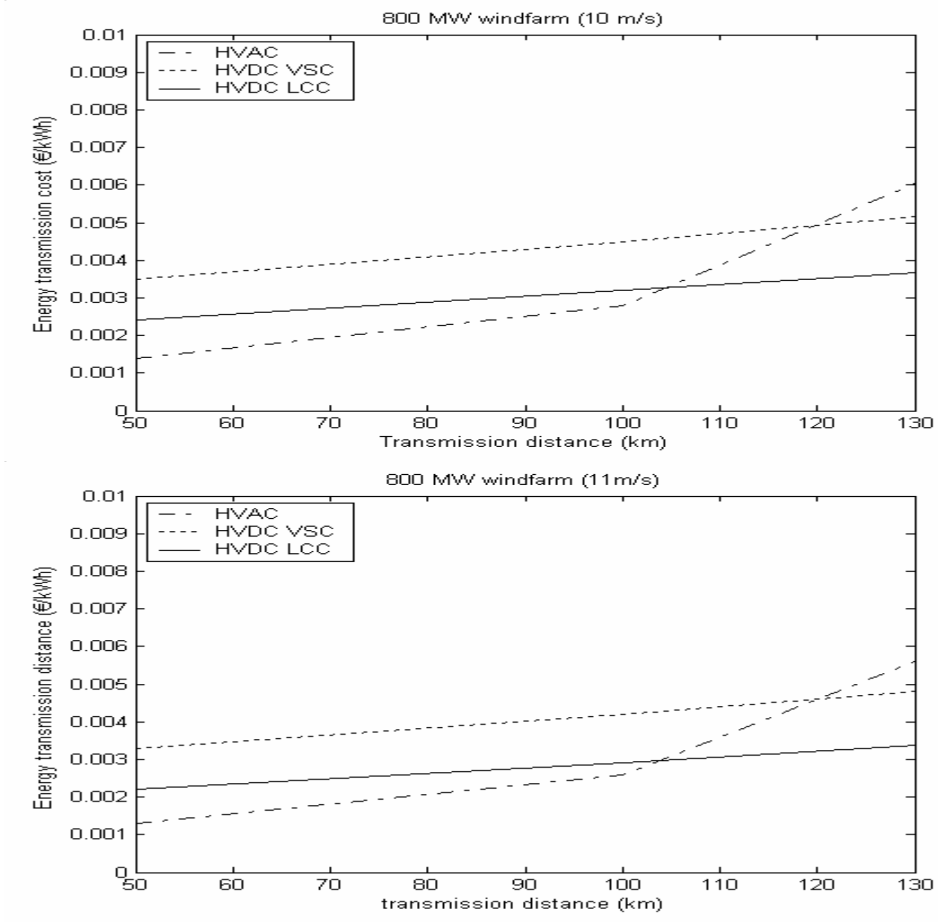
800 MW windfarm

10 and 11 m/sec average wind speed

50 – 300 km transmission length



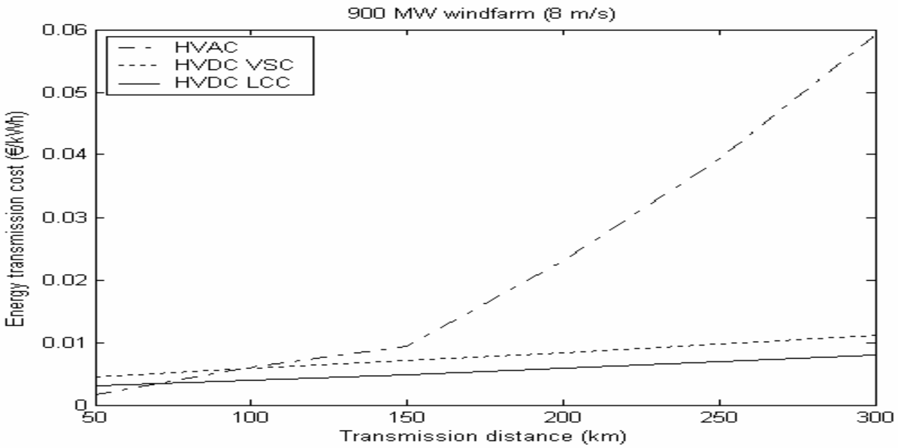
Detailed area

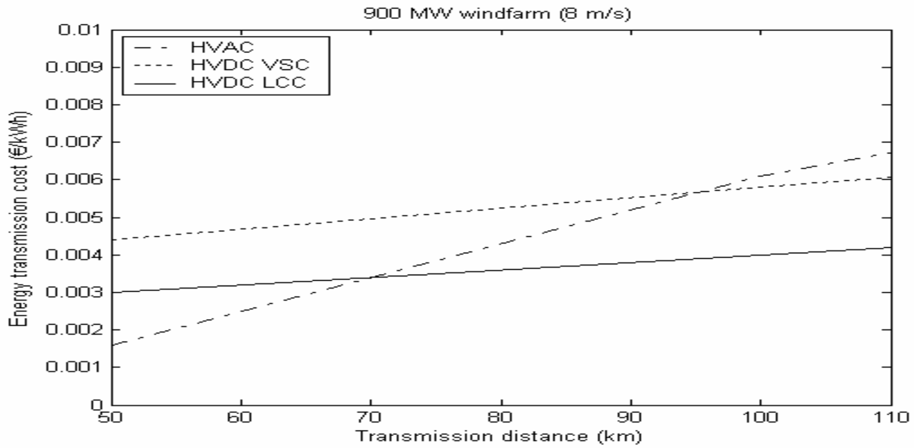


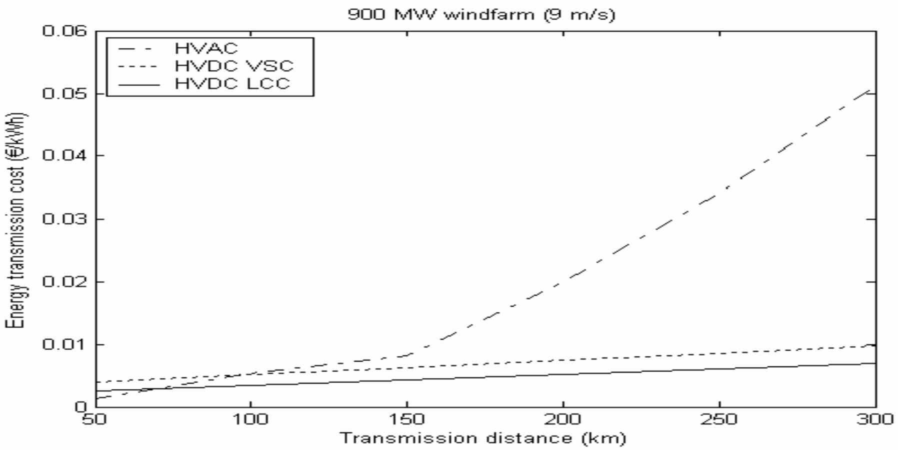
900 MW windfarm
8 and 9 m/sec average wind speed

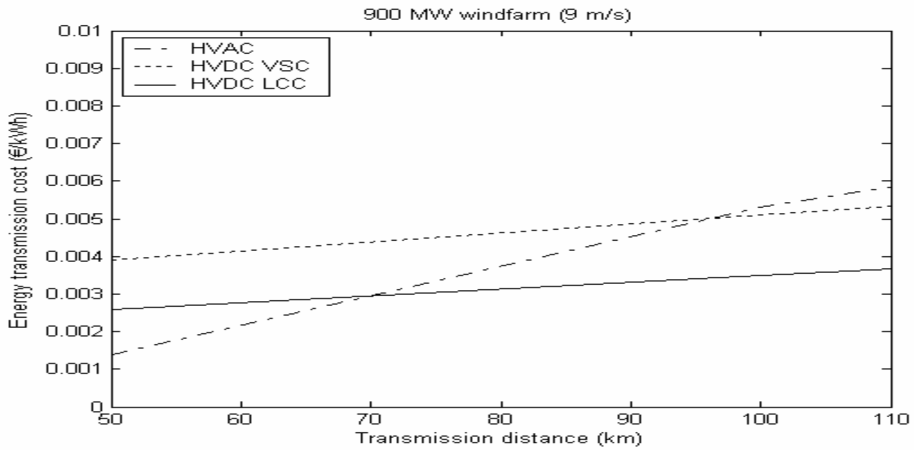
50 – 300 km transmission length

Detailed area





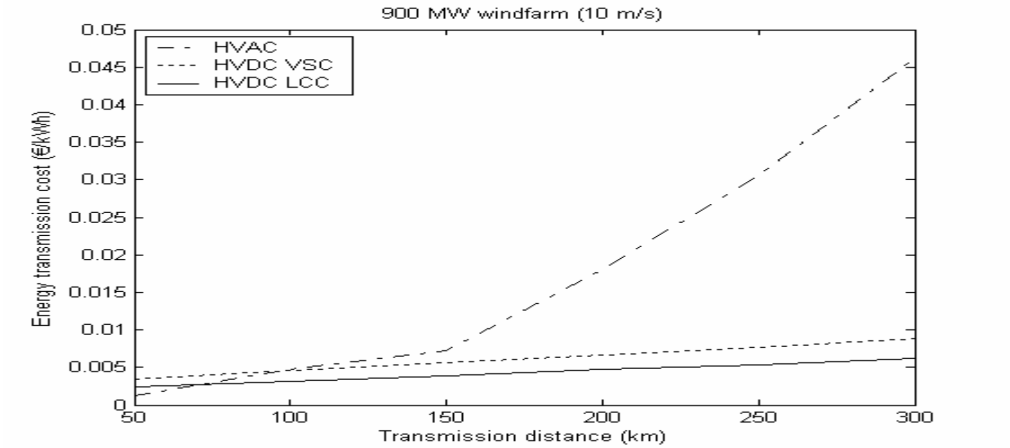


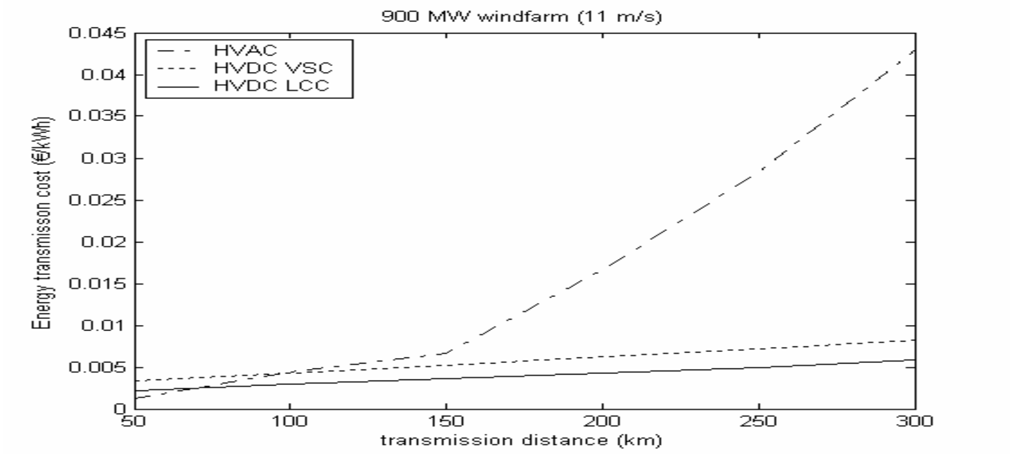


900 MW windfarm

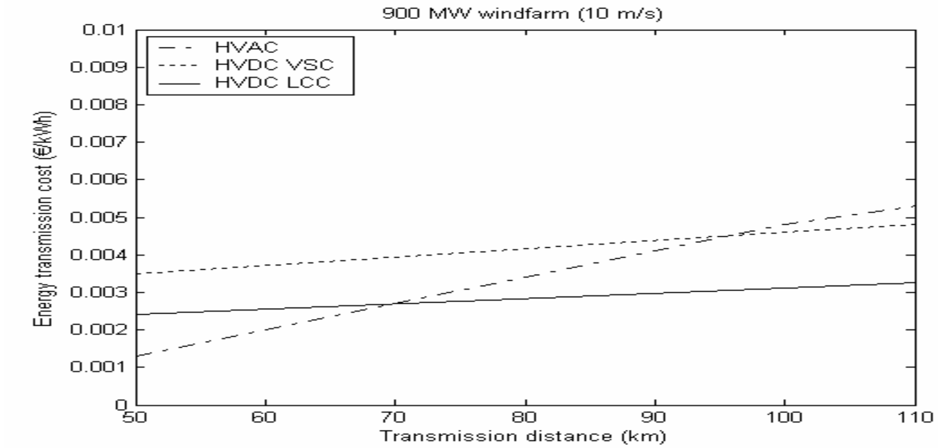
10 and 11 m/sec average wind speed

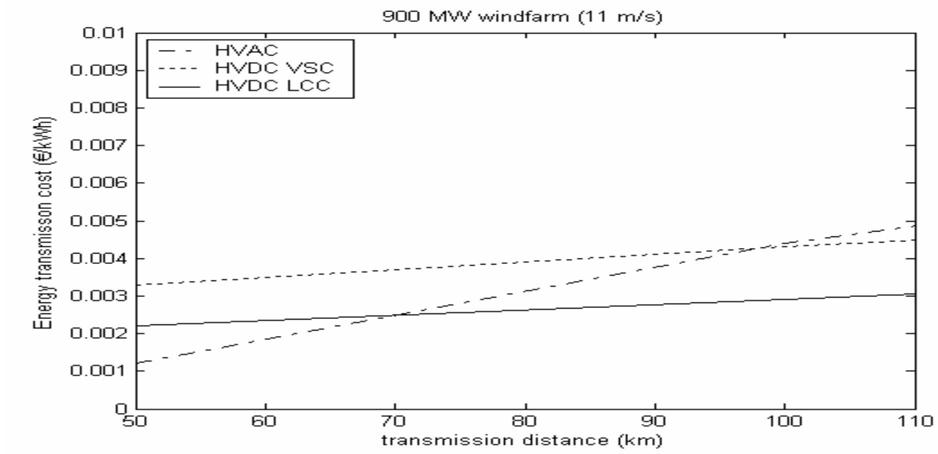
50 – 300 km transmission length





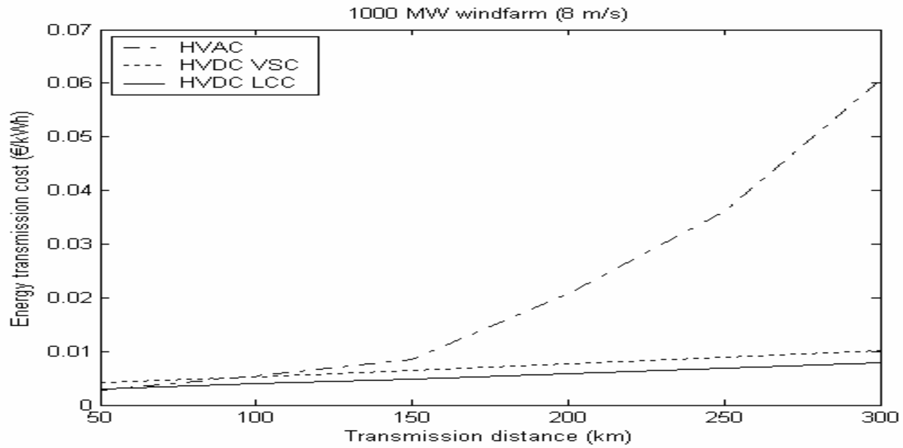
Detailed area

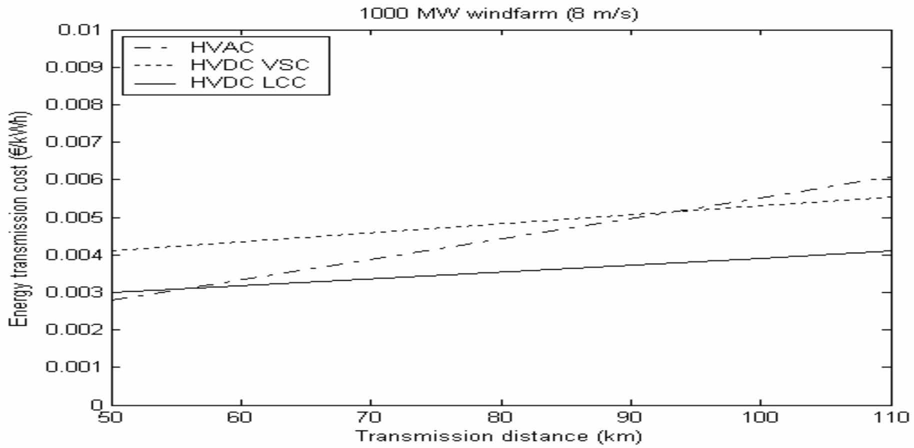


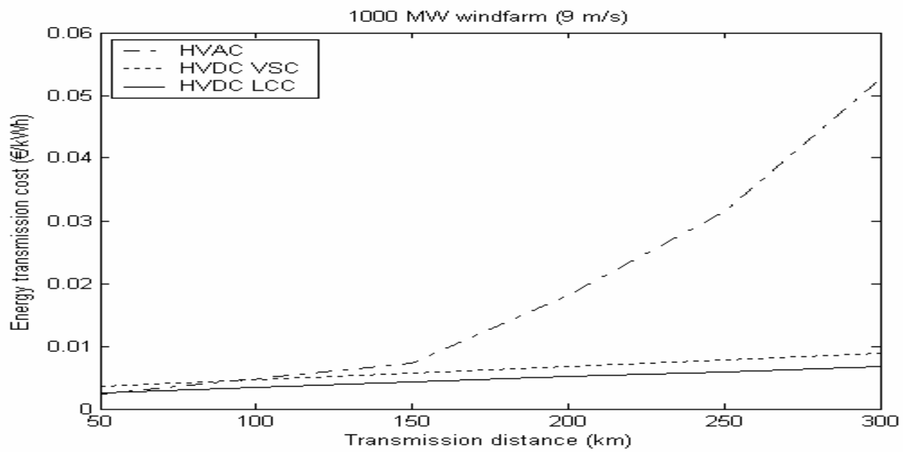


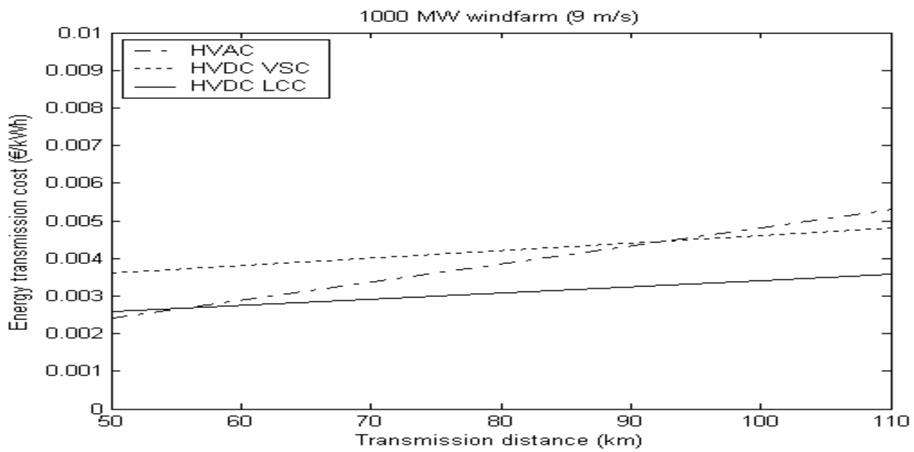
1000 MW windfarm
8 and 9 m/sec average wind speed
50 – 300 km transmission length

Detailed area



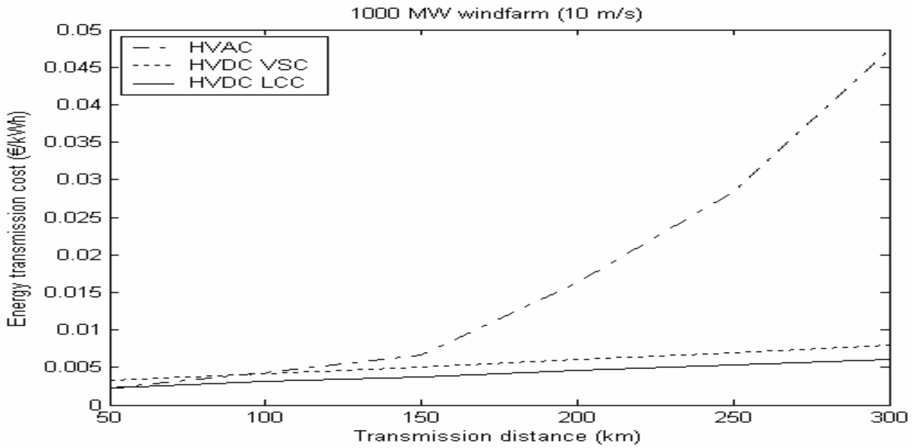


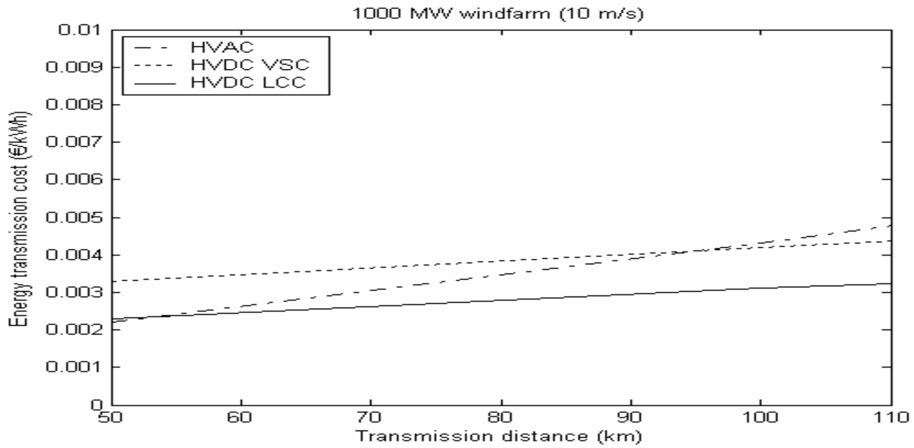


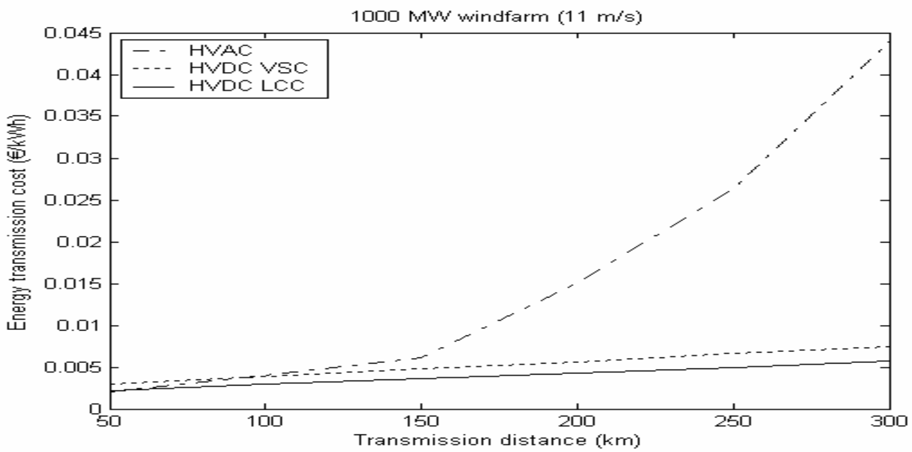


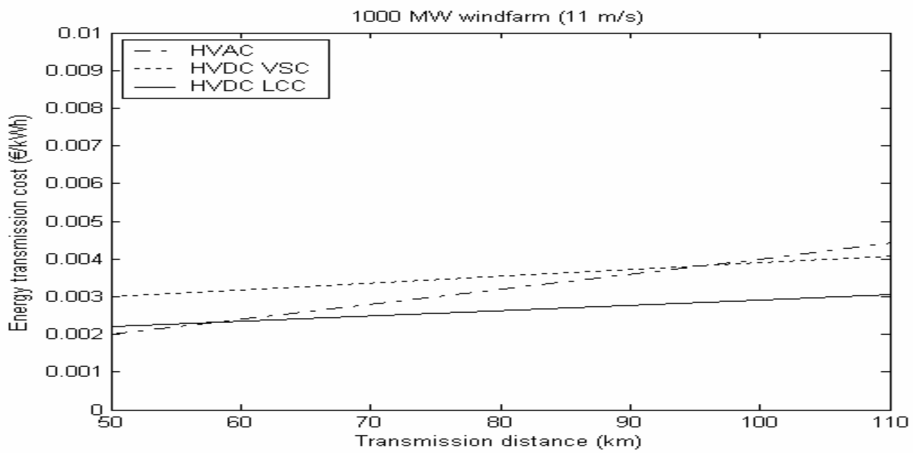
1000 MW windfarm
10 and 11 m/sec average wind speed
50 – 300 km transmission length

Detailed area









Appendix F
Tables for the Energy Transmission Cost of HVAC, HVDC VSC and HVDC LCC Transmission Systems for 10% interest rate

Inputs in bold indicate lowest energy transmission cost for specific transmission technology, distance and average wind speed

400 MW windfarm

€/kWh	HVAC											
	132kV				220 kV				400 kV			
	8 m/s	9m/s	10m/s	11m/s	8 m/s	9m/s	10m/s	11m/s	8 m/s	9m/s	10m/s	11m/s
50 km	0.0114	0.0099	0.0089	0.0083	0.0123	0.0107	0.0096	0.0089	0.0073	0.0063	0.0057	0.0053
100 km	0.0229	0.0199	0.0180	0.0167	0.0248	0.0215	0.0194	0.0179	**0.0145**	**0.0125**	**0.0113**	**0.0104**
150 km	0.0353	0.0307	0.0277	0.0257	0.0385	0.0334	0.0300	0.0277	**0.0223**	**0.0193**	**0.0173**	**0.0160**
200 km	**0.0490**	**0.0427**	**0.0385**	**0.0358**	0.0544	0.0470	0.0422	0.0390	0.1014	0.0871	0.0780	0.0719
250 km	**0.0933**	**0.0809**	**0.0728**	**0.0674**	0.1154	0.0991	0.0886	0.0817	-	-	-	-
300 km	**0.1212**	**0.1050**	**0.0945**	**0.0874**	-	-	-	-	-	-	-	-

Modified Case A

395 MW windfarm , Transmission Voltage: **220 kV**, Transmission Distance **50 km**				
Need for one 220 kV cable (2 needed in the non-modified version above)				
Average wind speed	8 m/s	9 m/s	10 m/s	11 m/s
Transmission Cost (€/kWh)	**0.0065**	**0.0057**	**0.0051**	**0.0047**

€/kWh	HVDC VSC											
	2x220 MW CS, 2x220 MW CP				500 MW CS, 1x500 MW CP				2x220 MW CS, 1x500 MW CP			
	8 m/s	9m/s	10m/s	11m/s	8 m/s	9m/s	10m/s	11m/s	8 m/s	9m/s	10m/s	11m/s
50 km	0.0105	0.0092	0.0083	0.0077	0.0112	0.0097	0.0087	0.0080	**0.0099**	**0.0086**	**0.0077**	**0.0072**
100 km	0.0142	0.0124	0.0112	0.0104	0.0143	0.0124	0.0111	0.0103	**0.0129**	**0.0112**	**0.0101**	**0.0094**
150 km	0.0180	0.0156	0.0141	0.0131	0.0174	0.0151	0.0136	0.0126	**0.0159**	**0.0139**	**0.0125**	**0.0116**
200 km	0.0217	0.0189	0.0171	0.0159	0.0206	0.0179	0.0161	0.0149	**0.0190**	**0.0166**	**0.0150**	**0.0139**
250 km	0.0256	0.0223	0.0202	0.0187	0.0239	0.0207	0.0187	0.0173	**0.0222**	**0.0193**	**0.0174**	**0.0162**
300 km	0.0294	0.0257	0.0232	0.0216	0.0272	0.0236	0.0213	0.0197	**0.0254**	**0.0221**	**0.0200**	**0.0185**

€/kWh	HVDC LCC											
	440 CS				500 CS				2x250 CS			
	8 m/s	9m/s	10m/s	11m/s	8 m/s	9m/s	10m/s	11m/s	8 m/s	9m/s	10m/s	11m/s
50 km	**0.0069**	**0.0060**	**0.0054**	**0.0050**	0.0078	0.0068	0.0061	0.0056	0.0083	0.0072	0.0065	0.0060
100 km	**0.0092**	**0.0080**	**0.0072**	**0.0066**	0.0103	0.0089	0.0080	0.0074	0.0113	0.0098	0.0088	0.0082
150 km	**0.0114**	**0.0099**	**0.0089**	**0.0083**	0.0128	0.0111	0.0100	0.0093	0.0143	0.0124	0.0112	0.0103
200 km	**0.0137**	**0.0119**	**0.0107**	**0.0099**	0.0153	0.0133	0.0120	0.0111	0.0173	0.0150	0.0135	0.0126
250 km	**0.0160**	**0.0139**	**0.0125**	**0.0116**	0.0179	0.0155	0.0140	0.0129	0.0203	0.0177	0.0159	0.0148
300 km	**0.0184**	**0.0159**	**0.0144**	**0.0133**	0.0204	0.0177	0.0160	0.0148	0.0234	0.0204	0.0184	0.0170

500 MW windfarm

€/kWh	HVAC											
	132kV				220 kV				400 kV			
	8 m/s	9m/s	10m/s	11m/s	8 m/s	9m/s	10m/s	11m/s	8 m/s	9m/s	10m/s	11m/s
50 km	0.0135	0.0117	0.0106	0.0098	0.0099	0.0086	0.0078	0.0072	**0.0058**	**0.0051**	**0.0046**	**0.0042**
100 km	0.0271	0.0236	0.0212	0.0197	0.0200	0.0173	0.0156	0.0145	**0.0116**	**0.0101**	**0.0090**	**0.0084**
150 km	0.0417	0.0362	0.0327	0.0303	0.0310	0.0269	0.0242	0.0224	**0.0178**	**0.0154**	**0.0138**	**0.0128**
200 km	0.0578	0.0502	0.0453	0.0420	**0.0436**	**0.0378**	**0.0340**	**0.0314**	0.1076	0.0927	0.0831	0.0766
250 km	**0.0760**	**0.0661**	**0.0596**	**0.0553**	0.0901	0.0776	0.0695	0.0642	-	-	-	-
300 km	**0.1281**	**0.1110**	**0.0999**	**0.0926**	-	-	-	-	-	-	-	-

Modified Case B

475 MW windfarm , Transmission Voltage: 132 kV, Transmission Distance 50 km				
Need for two 132 kV cable (3 needed in the non-modified version above)				
Average wind speed	8 m/s	9 m/s	10 m/s	11 m/s
Transmission Cost (€/kWh)	0.0097	0.0085	0.0076	0.0071

€/kWh	HVDC VSC											
	350+220 MW CS, 350+220 MW CP				2x350 MW CS, 2x350 MW CP				1x500 MW CS,1x500 MW CP			
	8 m/s	9m/s	10m/s	11m/s	8 m/s	9m/s	10m/s	11m/s	8 m/s	9m/s	10m/s	11m/s
50 km	0.0104	0.0091	0.0082	0.0076	0.0122	0.0107	0.0096	0.0089	**0.0089**	**0.0077**	**0.0070**	**0.0064**
100 km	0.0138	0.0120	0.0108	0.0101	0.0160	0.0139	0.0125	0.0116	**0.0114**	**0.0099**	**0.0089**	**0.0082**
150 km	0.0172	0.0150	0.0135	0.0126	0.0197	0.0172	0.0155	0.0144	**0.0140**	**0.0121**	**0.0109**	**0.0101**
200 km	0.0206	0.0180	0.0163	0.0151	0.0235	0.0205	0.0185	0.0171	**0.0166**	**0.0144**	**0.0129**	**0.0120**
250 km	0.0242	0.0211	0.0190	0.0177	0.0273	0.0238	0.0215	0.0200	**0.0192**	**0.0167**	**0.0150**	**0.0139**
300 km	0.0277	0.0242	0.0219	0.0203	0.0312	0.0272	0.0246	0.0228	**0.0219**	**0.0190**	**0.0171**	**0.0159**
€/kWh	350+220 MW CS, 1x500 MW CP				2x350 MW CS, 1x500 MW CP							
	8 m/s	9m/s	10m/s	11m/s	8 m/s	9m/s	10m/s	11m/s	8 m/s	9m/s	10m/s	11m/s
50 km	0.0095	0.0083	0.0075	0.0069	0.0109	0.0095	0.0086	0.0080				
100 km	0.0119	0.0104	0.0094	0.0087	0.0133	0.0116	0.0105	0.0097				
150 km	0.0144	0.0125	0.0113	0.0105	0.0158	0.0137	0.0124	0.0115				
200 km	0.0169	0.0147	0.0133	0.0123	0.0183	0.0159	0.0143	0.0133				
250 km	0.0194	0.0169	0.0153	0.0142	0.0208	0.0181	0.0163	0.0152				
300 km	0.0220	0.0192	0.0174	0.0161	0.0233	0.0203	0.0184	0.0170				

€/kWh	HVDC LCC											
	500 CS				2 x 250 CS				600 CS			
	8 m/s	9m/s	10m/s	11m/s	8 m/s	9m/s	10m/s	11m/s	8 m/s	9m/s	10m/s	11m/s
50 km	**0.0062**	**0.0054**	**0.0049**	**0.0045**	0.0066	0.0058	0.0052	0.0048	0.0074	0.0064	0.0058	0.0054
100 km	**0.0082**	**0.0071**	**0.0064**	**0.0060**	0.0090	0.0079	0.0071	0.0066	0.0097	0.0084	0.0076	0.0070
150 km	**0.0102**	**0.0089**	**0.0080**	**0.0074**	0.0115	0.0100	0.0090	0.0083	0.0120	0.0104	0.0094	0.0087
200 km	**0.0123**	**0.0107**	**0.0096**	**0.0089**	0.0139	0.0121	0.0109	0.0101	0.0143	0.0124	0.0112	0.0104
250 km	**0.0143**	**0.0124**	**0.0112**	**0.0104**	0.0164	0.0143	0.0129	0.0119	0.0167	0.0145	0.0130	0.0121
300 km	**0.0164**	**0.0142**	**0.0128**	**0.0119**	0.0189	0.0164	0.0148	0.0138	0.0190	0.0165	0.0149	0.0138

600 MW windfarm

€/kWh	HVAC											
	132kV				220 kV				400 kV			
	8 m/s	9m/s	10m/s	11m/s	8 m/s	9m/s	10m/s	11m/s	8 m/s	9m/s	10m/s	11m/s
50 km	0.0114	0.0099	0.0089	0.0082	0.0084	0.0073	0.0066	0.0061	**0.0049**	**0.0043**	**0.0038**	**0.0036**
100 km	0.0229	0.0199	0.0179	0.0166	0.0168	0.0146	0.0132	0.0122	**0.0097**	**0.0084**	**0.0076**	**0.0070**
150 km	0.0352	0.0307	0.0277	0.0257	0.0260	0.0226	0.0204	0.0189	**0.0148**	**0.0128**	**0.0115**	**0.0107**
200 km	**0.0490**	**0.0427**	**0.0385**	**0.0357**	0.0541	0.0469	0.0422	0.0391	0.1100	0.0952	0.0856	0.0792
250 km	**0.0831**	**0.0722**	**0.0651**	**0.0603**	0.1002	0.0864	0.0775	0.0716	-	-	-	-
300 km	**0.1323**	**0.1147**	**0.1034**	**0.0957**	-	-	-	-	-	-	-	-

€/kWh	HVDC VSC											
	2x350 MW CS, 2x350 MW CP				500+220 MW CS, 500+220 MW CP							
	8 m/s	9m/s	10m/s	11m/s	8 m/s	9m/s	10m/s	11m/s	8 m/s	9m/s	10m/s	11m/s
50 km	0.0103	0.0090	0.0081	0.0076	**0.0101**	**0.0088**	**0.0080**	**0.0074**				
100 km	0.0135	0.0117	0.0106	0.0099	**0.0128**	**0.0112**	**0.0101**	**0.0094**				
150 km	0.0167	0.0145	0.0131	0.0122	**0.0156**	**0.0136**	**0.0123**	**0.0114**				
200 km	0.0199	0.0174	0.0157	0.0146	**0.0184**	**0.0160**	**0.0145**	**0.0134**				
250 km	0.0232	0.0202	0.0183	0.0170	**0.0212**	**0.0185**	**0.0167**	**0.0155**				
300 km	0.0265	0.0231	0.0210	0.0195	**0.0241**	**0.0210**	**0.0190**	**0.0176**				

€/kWh	HVDC LCC											
	600 CS				440 CS + 250 CS				2 x 300 CS			
	8 m/s	9m/s	10m/s	11m/s	8 m/s	9m/s	10m/s	11m/s	8 m/s	9m/s	10m/s	11m/s
50 km	**0.0062**	**0.0054**	**0.0048**	**0.0045**	0.0073	0.0064	0.0057	0.0053	0.0065	0.0056	0.0051	0.0047
100 km	**0.0081**	**0.0070**	**0.0063**	**0.0059**	0.0098	0.0085	0.0077	0.0071	0.0087	0.0076	0.0069	0.0063
150 km	**0.0100**	**0.0087**	**0.0078**	**0.0072**	0.0123	0.0107	0.0096	0.0089	0.0110	0.0096	0.0086	0.0080
200 km	**0.0120**	**0.0104**	**0.0093**	**0.0087**	0.0148	0.0129	0.0116	0.0108	0.0133	0.0115	0.0104	0.0097
250 km	**0.0139**	**0.0121**	**0.0109**	**0.0101**	0.0174	0.0151	0.0136	0.0126	0.0156	0.0136	0.0123	0.0114
300 km	**0.0159**	**0.0138**	**0.0124**	**0.0115**	0.0199	0.0173	0.0156	0.0145	0.0180	0.0156	0.0141	0.0131

700 MW windfarm

€/kWh	HVAC											
	132kV				220 kV				400 kV			
	8 m/s	9m/s	10m/s	11m/s	8 m/s	9m/s	10m/s	11m/s	8 m/s	9m/s	10m/s	11m/s
50 km	0.0098	0.0086	0.0077	0.0072	0.0073	0.0063	0.0057	0.0053	**0.0042**	**0.0037**	**0.0033**	**0.0031**
100 km	0.0260	0.0226	0.0203	0.0188	0.0146	0.0127	0.0114	0.0106	**0.0083**	**0.0072**	**0.0065**	**0.0060**
150 km	0.0397	0.0346	0.0312	0.0289	0.0332	0.0288	0.0259	0.0240	0.0248	0.0215	0.0194	0.0180
200 km	0.0549	0.0477	0.0431	0.0400	**0.0465**	**0.0403**	**0.0363**	**0.0336**	0.0941	0.0813	0.0730	0.0674
250 km	**0.0723**	**0.0629**	**0.0569**	**0.0528**	0.0848	0.0732	0.0657	0.0608	-	-	-	-
300 km	**0.1143**	**0.0993**	**0.0896**	**0.0831**	-	-	-	-	-	-	-	-

Modified Case C

680 MW windfarm , Transmission Voltage: 220 kV, Transmission Distance 150 km				
Need for two 220 kV cable (3 needed in the non-modified version above)				
Average wind speed	8 m/s	9 m/s	10 m/s	11 m/s
Transmission Cost (€/kWh)	**0.0232**	**0.0202**	**0.0182**	**0.0169**

€/kWh	HVDC VSC											
	2x350 MW CS, 2x350 MW CP				500+220 MW CS, 500+220 MW CP							
	8 m/s	9m/s	10m/s	11m/s	8 m/s	9m/s	10m/s	11m/s	8 m/s	9m/s	10m/s	11m/s
50 km	0.0090	0.0078	0.0071	0.0066	**0.0088**	**0.0076**	**0.0069**	**0.0064**				
100 km	0.0117	0.0102	0.0092	0.0086	**0.0111**	**0.0097**	**0.0088**	**0.0082**				
150 km	0.0145	0.0127	0.0115	0.0106	**0.0135**	**0.0118**	**0.0107**	**0.0099**				
200 km	0.0173	0.0151	0.0137	0.0127	**0.0160**	**0.0139**	**0.0126**	**0.0117**				
250 km	0.0202	0.0177	0.0160	0.0149	**0.0185**	**0.0161**	**0.0146**	**0.0136**				
300 km	0.0232	0.0203	0.0184	0.0171	**0.0210**	**0.0183**	**0.0166**	**0.0154**				

€/kWh	HVDC LCC											
	500 CS + 250 CS				440 CS + 300 CS				3 x 250 CS			
	8 m/s	9m/s	10m/s	11m/s	8 m/s	9m/s	10m/s	11m/s	8 m/s	9m/s	10m/s	11m/s
50 km	0.0068	0.0059	0.0053	0.0049	0.0067	0.0058	0.0053	0.0049	0.0071	0.0062	0.0056	0.0051
100 km	0.0091	0.0079	0.0071	0.0066	0.0089	0.0078	0.0070	0.0065	0.0096	0.0084	0.0076	0.0070
150 km	0.0113	0.0099	0.0089	0.0082	0.0112	0.0097	0.0088	0.0081	0.0122	0.0106	0.0096	0.0089
200 km	0.0136	0.0119	0.0107	0.0099	0.0135	0.0117	0.0106	0.0098	0.0148	0.0129	0.0117	0.0108
250 km	0.0160	0.0139	0.0125	0.0116	0.0157	0.0137	0.0124	0.0115	0.0175	0.0152	0.0137	0.0127
300 km	0.0183	0.0159	0.0144	0.0133	0.0181	0.0157	0.0142	0.0131	0.0201	0.0175	0.0158	0.0147
€/kWh	600 CS + 130 CS											
	8 m/s	9m/s	10m/s	11m/s	8 m/s	9m/s	10m/s	11m/s	8 m/s	9m/s	10m/s	11m/s
50 km	**0.0066**	**0.0058**	**0.0052**	**0.0048**								
100 km	**0.0088**	**0.0077**	**0.0069**	**0.0064**								
150 km	**0.0111**	**0.0096**	**0.0087**	**0.0080**								
200 km	**0.0133**	**0.0116**	**0.0104**	**0.0097**								
250 km	**0.0156**	**0.0136**	**0.0122**	**0.0113**								
300 km	**0.0179**	**0.0155**	**0.0140**	**0.0130**								

800 MW windfarm

€/kWh	HVAC											
	132kV				220 kV				400 kV			
	8 m/s	9m/s	10m/s	11m/s	8 m/s	9m/s	10m/s	11m/s	8 m/s	9m/s	10m/s	11m/s
50 km	0.0113	0.0098	0.0089	0.0082	0.0094	0.0081	0.0073	0.0068	**0.0037**	**0.0032**	**0.0029**	**0.0027**
100 km	0.0228	0.0198	0.0179	0.0166	0.0188	0.0164	0.0147	0.0137	0.0143	0.0124	0.0112	0.0103
150 km	0.0352	0.0306	0.0277	0.0257	0.0291	0.0253	0.0228	0.0211	**0.0217**	**0.0189**	**0.0170**	**0.0157**
200 km	0.0487	0.0425	0.0384	0.0356	**0.0408**	**0.0354**	**0.0319**	**0.0296**	0.0981	0.0849	0.0763	0.0706
250 km	**0.0783**	**0.0681**	**0.0614**	**0.0570**	0.0741	0.0641	0.0576	0.0533	-	-	-	-
300 km	**0.1192**	**0.1036**	**0.0935**	**0.0866**	-	-	-	-	-	-	-	-

Modified Cases D, E

790 MW windfarm , Transmission Voltage: 220 kV, Transmission Distance **50 km**				
Need for two 220 kV cable (3 needed in the non-modified version above)				
Average wind speed	8 m/s	9 m/s	10 m/s	11 m/s
Transmission Cost (€/kWh)	0.0065	0.0057	0.0051	0.0047
795 MW windfarm , Transmission Voltage: 400 kV, Transmission Distance **100 km**				
Need for one 400 kV cable (2 needed in the non-modified version above)				
Average wind speed	8 m/s	9 m/s	10 m/s	11 m/s
Transmission Cost (€/kWh)	**0.0073**	**0.0063**	**0.0057**	**0.0053**

€/kWh	HVDC VSC											
	2x350+220 MW CS,2x 350+220 MW CP				3x350 MW CS, 3x350 MW CP				500+350 MW CS, 500+350 MW CP			
	8 m/s	9m/s	10m/s	11m/s	8 m/s	9m/s	10m/s	11m/s	8 m/s	9m/s	10m/s	11m/s
50 km	0.0102	0.0089	0.0081	0.0075	0.0113	0.0098	0.0089	0.0082	**0.0093**	**0.0081**	**0.0073**	**0.0068**
100 km	0.0134	0.0117	0.0106	0.0098	0.0147	0.0128	0.0116	0.0107	**0.0119**	**0.0104**	**0.0094**	**0.0088**
150 km	0.0167	0.0146	0.0132	0.0123	0.0182	0.0158	0.0143	0.0133	**0.0147**	**0.0128**	**0.0116**	**0.0108**
200 km	0.0200	0.0175	0.0158	0.0147	0.0216	0.0189	0.0170	0.0158	**0.0174**	**0.0152**	**0.0138**	**0.0128**
250 km	0.0234	0.0204	0.0185	0.0172	0.0252	0.0219	0.0198	0.0184	**0.0203**	**0.0177**	**0.0160**	**0.0149**
300 km	0.0268	0.0234	0.0212	0.0190	0.0288	0.0251	0.0227	0.0210	**0.0231**	**0.0202**	**0.0183**	**0.0170**

€/kWh	HVDC LCC											
	500 CS + 300 CS				2 x 440 CS				600 CS + 250 CS			
	8 m/s	9m/s	10m/s	11m/s	8 m/s	9m/s	10m/s	11m/s	8 m/s	9m/s	10m/s	11m/s
50 km	**0.0063**	**0.0055**	**0.0049**	**0.0046**	0.0069	0.0060	0.0054	0.0050	0.0067	0.0058	0.0052	0.0048
100 km	**0.0084**	**0.0073**	**0.0066**	**0.0061**	0.0091	0.0079	0.0071	0.0066	0.0088	0.0077	0.0069	0.0064
150 km	**0.0105**	**0.0091**	**0.0082**	**0.0076**	0.0113	0.0099	0.0089	0.0082	0.0110	0.0096	0.0086	0.0080
200 km	**0.0126**	**0.0110**	**0.0099**	**0.0092**	0.0136	0.0118	0.0107	0.0099	0.0132	0.0115	0.0104	0.0096
250 km	**0.0147**	**0.0128**	**0.0116**	**0.0107**	0.0159	0.0138	0.0124	0.0115	0.0154	0.0134	0.0121	0.0112
300 km	**0.0169**	**0.0147**	**0.0132**	**0.0123**	0.0181	0.0158	0.0142	0.0132	0.0176	0.0153	0.0139	0.0128

900 MW windfarm

€/kWh	HVAC											
	132kV				220 kV				400 kV			
	8 m/s	9m/s	10m/s	11m/s	8 m/s	9m/s	10m/s	11m/s	8 m/s	9m/s	10m/s	11m/s
50 km	0.0101	0.0088	0.0080	0.0074	0.0084	0.0073	0.0066	0.0061	0.0064	0.0056	0.0050	0.0046
100 km	0.0205	0.0178	0.0161	0.0149	0.0168	0.0146	0.0132	0.0122	**0.0127**	**0.0110**	**0.0099**	**0.0092**
150 km	0.0388	0.0337	0.0304	0.0282	0.0260	0.0226	0.0204	0.0189	**0.0193**	**0.0168**	**0.0151**	**0.0140**
200 km	0.0535	0.0466	0.0421	0.0390	**0.0480**	**0.0417**	**0.0375**	**0.0347**	0.1010	0.0875	0.0788	0.0730
250 km	**0.0827**	**0.0719**	**0.0648**	**0.0602**	0.0820	0.0709	0.0637	0.0589	-	-	-	-
300 km	**0.1231**	**0.1068**	**0.0964**	**0.0893**	-	-	-	-	-	-	-	-

Modified Cases F

885 MW windfarm , Transmission Voltage: 400 kV, Transmission Distance 50 km				
Need for one 400 kV cable (2 needed in the non-modified version above)				
Average wind speed	8 m/s	9 m/s	10 m/s	11 m/s
Transmission Cost (€/kWh)	**0.0033**	**0.0029**	**0.0026**	**0.0024**

€/kWh	HVDC VSC											
	3x350 MW CS, 3x350 MW CP				2x500 MW CS, 2x500 MW CP				2x350+220 MW CS,2x 350+220 MW CP			
	8 m/s	9m/s	10m/s	11m/s	8 m/s	9m/s	10m/s	11m/s	8 m/s	9m/s	10m/s	11m/s
50 km	0.0102	0.0089	0.0080	0.0074	0.0095	0.0083	0.0075	0.0070	**0.0092**	**0.0080**	**0.0073**	**0.0068**
100 km	0.0132	0.0116	0.0105	0.0097	0.0121	0.0106	0.0096	0.0089	**0.0121**	**0.0106**	**0.0096**	**0.0089**
150 km	0.0164	0.0143	0.0129	0.0120	**0.0148**	**0.0129**	**0.0117**	**0.0109**	0.0151	0.0132	0.0119	0.0111
200 km	0.0195	0.0171	0.0154	0.0143	**0.0175**	**0.0153**	**0.0139**	**0.0129**	0.0181	0.0158	0.0143	0.0133
250 km	0.0228	0.0199	0.0180	0.0167	**0.0203**	**0.0177**	**0.0160**	**0.0149**	0.0211	0.0185	0.0168	0.0156
300 km	0.0260	0.0227	0.0206	0.0191	**0.0231**	**0.0202**	**0.0183**	**0.0170**	0.0242	0.0212	0.0192	0.0179

€/kWh	HVDC LCC											
	3 x 300 CS				600 CS + 300 CS				500 CS + 440 CS			
	8 m/s	9m/s	10m/s	11m/s	8 m/s	9m/s	10m/s	11m/s	8 m/s	9m/s	10m/s	11m/s
50 km	0.0065	0.0056	0.0051	0.0047	**0.0062**	**0.0054**	**0.0049**	**0.0045**	0.0065	0.0057	0.0051	0.0047
100 km	0.0087	0.0076	0.0068	0.0063	**0.0083**	**0.0072**	**0.0065**	**0.0060**	0.0086	0.0075	0.0067	0.0062
150 km	0.0110	0.0096	0.0086	0.0080	**0.0103**	**0.0089**	**0.0081**	**0.0075**	0.0107	0.0093	0.0084	0.0078
200 km	0.0133	0.0116	0.0104	0.0097	**0.0123**	**0.0107**	**0.0097**	**0.0090**	0.0128	0.0111	0.0100	0.0093
250 km	0.0156	0.0136	0.0122	0.0114	**0.0144**	**0.0125**	**0.0113**	**0.0105**	0.0149	0.0130	0.0117	0.0109
300 km	0.0179	0.0156	0.0141	0.0131	**0.0165**	**0.0143**	**0.0129**	**0.0120**	0.0171	0.0149	0.0134	0.0124

1000 MW windfarm

€/kWh	HVAC											
	132kV				220 kV				400 kV			
	8 m/s	9m/s	10m/s	11m/s	8 m/s	9m/s	10m/s	11m/s	8 m/s	9m/s	10m/s	11m/s
50 km	0.0113	0.0098	0.0089	0.0082	0.0076	0.0066	0.0060	0.0055	**0.0058**	**0.0050**	**0.0045**	**0.0042**
100 km	0.0228	0.0198	0.0179	0.0166	0.0152	0.0133	0.0120	0.0111	**0.0114**	**0.0099**	**0.0090**	**0.0083**
150 km	0.0351	0.0306	0.0276	0.0256	0.0237	0.0206	0.0186	0.0172	**0.0174**	**0.0151**	**0.0136**	**0.0126**
200 km	0.0486	0.0424	0.0384	0.0356	**0.0433**	**0.0376**	**0.0339**	**0.0314**	0.0909	0.0787	0.0708	0.0656
250 km	**0.0753**	**0.0656**	**0.0592**	**0.0550**	0.0883	0.0765	0.0688	0.0636	-	-	-	-
300 km	**0.1259**	**0.1095**	**0.0988**	**0.0915**	-	-	-	-	-	-	-	-

€/kWh	HVDC VSC											
	3x350 MW CS, 3x350 MW CP				2x500 MW CS, 2x500 MW CP							
	8 m/s	9m/s	10m/s	11m/s	8 m/s	9m/s	10m/s	11m/s	8 m/s	9m/s	10m/s	11m/s
50 km	0.0093	0.0081	0.0073	0.0068	**0.0086**	**0.0075**	**0.0068**	**0.0063**				
100 km	0.0121	0.0106	0.0096	0.0089	**0.0110**	**0.0096**	**0.0087**	**0.0081**				
150 km	0.0150	0.0131	0.0118	0.0110	**0.0135**	**0.0118**	**0.0107**	**0.0099**				
200 km	0.0179	0.0156	0.0142	0.0132	**0.0159**	**0.0139**	**0.0126**	**0.0117**				
250 km	0.0208	0.0182	0.0165	0.0154	**0.0185**	**0.0162**	**0.0146**	**0.0136**				
300 km	0.0239	0.0209	0.0189	0.0176	**0.0210**	**0.0184**	**0.0167**	**0.0155**				

€/kWh	HVDC LCC											
	2 x 500 CS				600 CS + 440 CS				500 CS + 600 CS			
	8 m/s	9m/s	10m/s	11m/s	8 m/s	9m/s	10m/s	11m/s	8 m/s	9m/s	10m/s	11m/s
50 km	**0.0062**	**0.0054**	**0.0049**	**0.0045**	0.0064	0.0056	0.0050	0.0047	0.0068	0.0059	0.0053	0.0049
100 km	**0.0082**	**0.0071**	**0.0064**	**0.0059**	0.0084	0.0073	0.0066	0.0061	0.0089	0.0077	0.0070	0.0065
150 km	**0.0102**	**0.0088**	**0.0080**	**0.0074**	0.0105	0.0091	0.0082	0.0076	0.0110	0.0096	0.0086	0.0080
200 km	**0.0122**	**0.0106**	**0.0096**	**0.0089**	0.0125	0.0109	0.0098	0.0091	0.0132	0.0115	0.0103	0.0096
250 km	**0.0142**	**0.0123**	**0.0111**	**0.0103**	0.0146	0.0127	0.0115	0.0106	0.0153	0.0133	0.0120	0.0112
300 km	**0.0162**	**0.0141**	**0.0127**	**0.0118**	0.0167	0.0145	0.0131	0.0122	0.0175	0.0152	0.0137	0.0127
€/kWh	2 x 600 CS											
	8 m/s	9m/s	10m/s	11m/s	8 m/s	9m/s	10m/s	11m/s	8 m/s	9m/s	10m/s	11m/s
50 km	0.0073	0.0064	0.0058	0.0053								
100 km	0.0096	0.0083	0.0075	0.0070								
150 km	0.0119	0.0103	0.0093	0.0086								
200 km	0.0142	0.0123	0.0111	0.0103								
250 km	0.0165	0.0143	0.0129	0.0120								
300 km	0.0188	0.0163	0.0147	0.0137								

Appendix G

List of Major Assumption

Chapter 3

- The wind speed follows the Rayleigh distribution.

Chapter 4

- The losses in the HVAC systems do not change after modifying the rated power of the transformers.

Chapter 5

- The reliability data for the components of the three transmission technologies will be the same in the offshore environment.
- The availability of the windfarm is 100%.
- In a serial system if one component fails then no failure can occur to the rest. The states in which failures occur to the components of a serial system are disjoint.
- In parallel systems failures in one system is independent of failures in the other parallel system for all of their components (cables included).
- Failures in cables are considered only as electrical and not caused by external factors (anchors, fishing nets etc).
- Voltage Source Converters have the same availability as STATCOMs.
- The availability of the cables used in HVDC VSC is the same with the cables used in HVDC LCC.
- Only basic components such as transformers, converters, and cable pair are considered in the energy availability study of HVDC VSC.
- XLPE three-core cables have the same availability as cables used in HVDC LCC cases.
- Losses of the transmission systems are not considered in the energy availability study.

Chapter 6

- An assumption for the cost of 400 kV XLPE submarine cable is used.
- Cost of compensator assumed to be 2/3 of the cost of the transformer with the same power rating.
- Cost for cable installation assumed to be 100,000 €/km for all cable types.