

# Electricity Transmission and Distribution

## HIGHLIGHTS

■ **PROCESS AND TECHNOLOGY STATUS** – In general, transmission systems are used for transporting large blocks of electricity over long distance (higher voltage) from power plants to local substations closer to the final customers, while distribution systems are used for delivering electricity over shorter distances (lower voltage) from these substations to final consumers [1,2, 5]. High voltage (HV) electricity can be transmitted as alternating current (AC) or direct current (DC). There are several advantages of using HVDC systems over HVAC for transporting large volumes of electricity over long distances [4, 7]: lower losses, lower investment costs, less land space, easier to control the active power in the link, etc. In 2012, HVDC transmission lines globally reach 195 GW of capacity with another 133 GW of capacity planned in about 65 projects [6]. These projects range from 100 MW of capacity to 7000 MW. The configuration of electric transmission and distribution (T&D) systems vary across regions. In the US, three grids represent about 275,000 km of high-voltage (> 200 kV) transmission lines (3,800 km of 765 kV AC lines and more than 4,800 km of 500 kV DC lines) and 9.7 million km of low-voltage distribution lines [10]. In the European Union, there are four interconnected HV transmission systems, 4 million distribution transformers, 10 million km of distribution power lines (97% of all power lines in Europe) that are linked to the transmission network by 10,700 interconnection points [5].

■ **PERFORMANCE AND COSTS** – Energy losses are measured as the fraction of the transported energy that is lost mainly due to line heating. Losses are lower in HVDC than in HVAC over long distances: for a  $\pm 800$  kV line voltage, losses are about 3% per 1,000 km for an HVDC while they are about 7% per 1,000 km for an HVAC line [4]. For HVDC sea cables, losses are about the same but can reach 60% per 100 km for a 750 kV HVAC sea cable. Most of the total T&D losses occur in the distribution systems. It has been falling significantly in the US from 16% in 1926 to 7% today [10] and in other developed countries (5.1% to 7.7% in 2010). In developing countries, losses vary between 11.6% and 20.7% for 2010 [8]. Emission factors associated to T&D losses are derived as a percentage of the total electricity generated in a region or a country [11]: it varies between 5% in OECD countries and up to 20% in developing countries. The cost of HVDC transmission systems vary widely with its design as well as the economic, geographical and environmental conditions. For a bipolar HVDC line, a cost of 190 k€/km is estimated and converter stations are estimated to 190 M€. For a double AC line, a cost of 190 k€/km (each) is estimated and AC substations (above 600 km) are estimated to 60 M€ [7]. The relation between cost and capacity (MW) is not linear. Another source [13] gives cost data per MW-km: 746\$ -3318\$ for long distance and 1491\$-6636\$ for lower voltage transmission lines. Substation costs vary between 10,700–24,000 \$/MW. Investment in transmission systems are higher in scenarios with higher renewable shares. Advanced metering infrastructure (AMI) brings significant operational benefits in distribution systems, although they do not cover the full investment costs: 150\$ to 400\$ per meter [7].

■ **POTENTIAL AND BARRIERS** – In many countries, the existing infrastructure for electricity transmission and distribution is aging and becoming obsolete or overstressed with the increasing penetration of intermittent renewables-based electricity sources. Projected investments in the electricity sector over the 2012-2035 period for the global generating capacity reaches about \$9.7 trillion dollars, with an additional \$7.2 trillion for T&D grids (40% to replace existing infrastructure and 60% to build new infrastructure) [1]. Depending on the region, the cost for transmission infrastructure varies between 4%-15% of the total cost and between 27%-34% for the distribution infrastructure. Potential savings resulting from grid modernization are significant with a benefit-to-cost ratio of between 4:1 and 6:1 ratios [9]. Many challenges will affect the electricity grids of many countries on the long term [10]. In particular, investment in improving flexibility within the system will become increasingly important with the penetration of intermittent forms of energy. This will involve modifications in the designs and operations of systems as well as reforms in the processes for transmission planning and system expansion. The penetration of electric vehicles and increasing changes in demand variability will accelerate the decline in capacity utilization and consequently increase electricity costs. The penetration of distributed generation (subsidies provided by net metering) will involve modifications in the design and operation of distribution systems. In relation with the future challenge, the industry faces a near-term shortage of skilled workers, such as engineers. New technologies and policies for reliability and efficiency will need to be developed and deployed to enhance observation and control in T&D systems as well as to make demand more responsive to real-time costs.

## PROCESS AND TECHNOLOGY STATUS

There are two main types of electricity networks: in general, **transmission systems** are used for transporting large blocks of high-voltage (HV) electricity over long distance from power plants to local substations that are closer to the final customers, while **distribution systems** are used for delivering lower voltage (LV) electricity over shorter distances, from substations to final consumers (households, businesses and small industrial facilities) [1, 2, 5]. In addition, HV electricity can be transmitted in a unidirectional way (direct current - DC) or with periodically reverse directions (alternating current - AC).

Energy flows in transmission and distribution lines are measured in term of power, i.e. the product of current and voltage [10]:

- Voltage: the capacity of a device to perform work per unit of charge that flows between two points, normally expressed in volts (V) or kilovolts (kV).
- Current: the rate of flow of charge through a conductor, normally expressed in amperes.

AC voltage and current waveforms are defined by three parameters (amplitude, frequency and phase) and the maximum value of the waveform is called “amplitude” (Figure 1) [10]. Higher power is transmitted through higher voltage lines. Indeed, “... since power loss is equal to the resistance of a conductor times the square of the current, loss in a transmission line can be reduced by increasing the transmission voltage, which allows the current to be reduced for the same amount of power transmitted.” [10]. In AC lines, voltage and current oscillate rapidly (many times a second), so as the instantaneous power (Figure 2). Consequently, it is useful to have different measures from multiple cycle averages:

- Real power (active power or average power) measured in watts: This is the measure of the instantaneous power. When voltage and current are in-phase, the instantaneous power is always positive and flowing in one direction (Figure 2b).
- Reactive power measured in volt-amperes reactive (VAR): This is happening when one waveform is shifted in time and creating an out-of-phase situation where power can have positive and negative values (Figure 2a-2c-2d). While the real power is moving in one direction, there are additional back and forth movements of the reactive power. This situation is created by reactance of the transmission line (energy stored in electric and magnetic fields created by voltages and currents respectively) and causes power losses in the system.
- Apparent power measured in volt amperes: This is the product of root-mean-square voltage and root-mean-square current. The ratio real power/apparent power is called “power factor.”

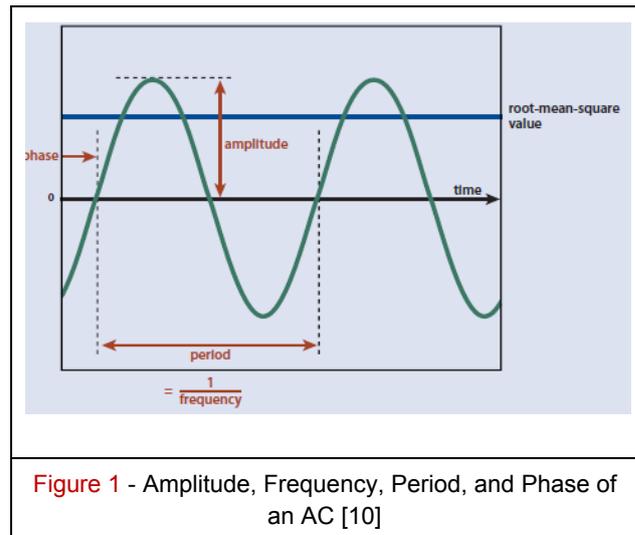
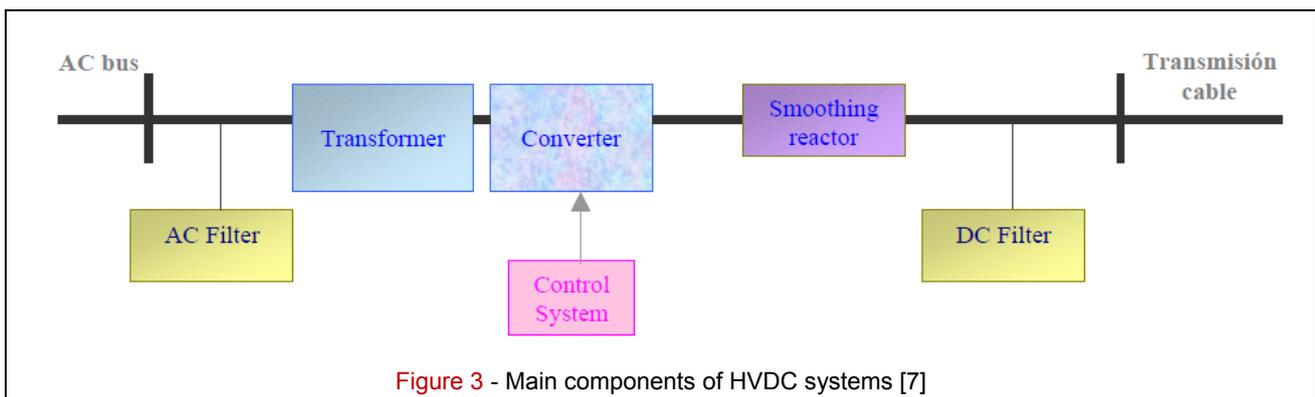
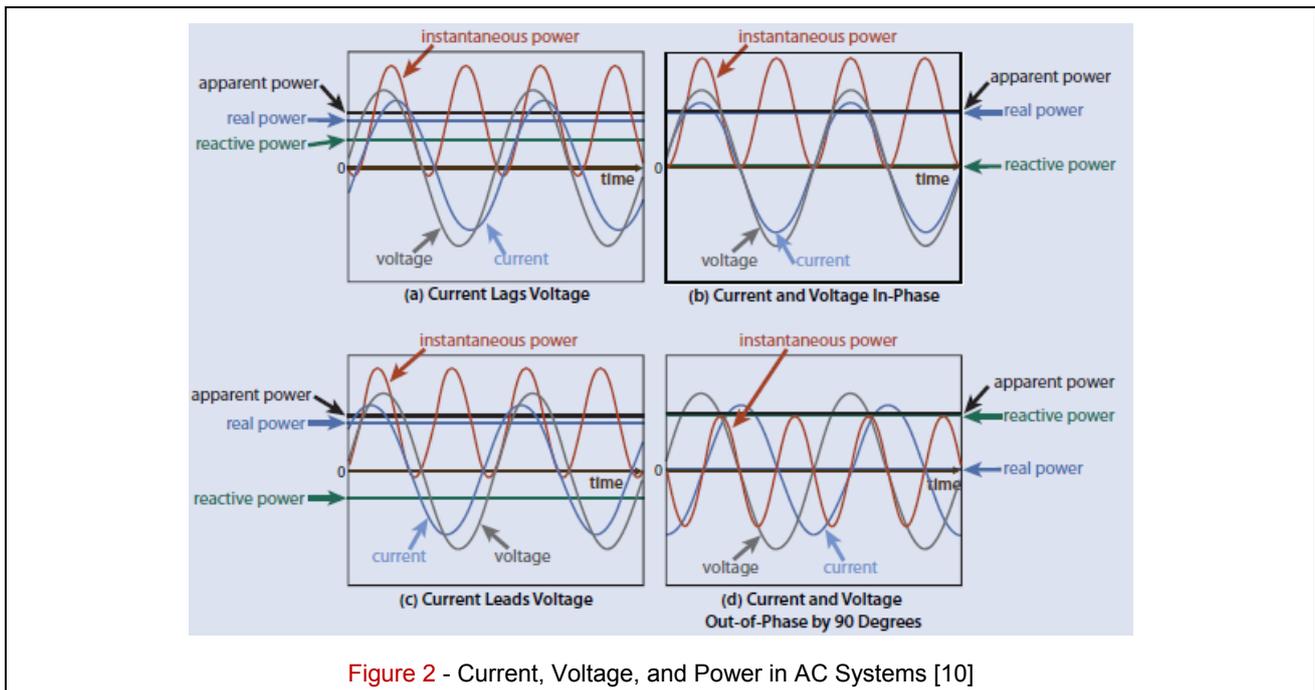


Figure 1 - Amplitude, Frequency, Period, and Phase of an AC [10]

■ **Existing Technologies** - Large amount of electricity can be transported between two regions by HVDC transmission lines (point-to-point configurations) [7]. Traditional HVDC systems are built with *line commutated current source converters*, which need a voltage source (synchronous generators or synchronous condensers) in the AC network at both ends. The main components of the HVDC systems are (Figure 3): the *valves* making the AC to DC conversion; the *converter transformers* transforming the voltage level of the AC; the *smoothing reactor, filter circuits, surge arrester, DC transmission circuit, control and protection* equipment [7]. Valves and control equipment are located in a closed, temperature-controlled building, while transformers, filters and phase correction capacitors are located outside and require significant space.

HVDC lines can be monopolar or bipolar systems: *monopolar systems* use one HV conductor and ground return; *bipolar systems* use two conductors with plus and minus polarity, and a grounded mid-point. There are economic advantages of using monopolar systems, but also security issues due to corrosion of pipelines caused by the ground current [7]. Monopolar systems are used in Europe, mainly for submarine lines.

The design of HVDC systems is influenced by many factors [7]: amounts of power to be transmitted, distance, voltage levels, overload, network characteristics on the receiving end, environmental rules, etc. After the design phase, the construction phase (contract date to commissioning) can take from one year up to three year for large systems. Regarding the operation activities aiming at keeping the system at designed availability levels, HVDC links can be operated remotely, and modern HVDC systems are designed to operate completely unmanned.



Consequently, their installation is not constrained by the labour force. Maintenance of HVDC and HVAC systems is comparable as the high voltage equipment in converter stations is similar and requires trained technicians. Normal maintenance is recommended for about one week a year, but can be extended to two years [7]. Bipolar systems can continue to operate during maintenance as only one pole is at stopped at the same time. Preventive maintenance should also be done in addition to the normal routine mainly to make sure the “equipment achieve optimally balanced availability with regard to the costs of maintenance, operating disturbances and planned outages”. The objective should normally to achieve 98% of availability [7]. The labour force required for maintenance varies based on several factors (regulations, unions, etc.).

Using the DC and high voltage (HVDC) for transporting

large volumes of electricity over long distances offers several advantages over AC [4, 7]:

- Lower losses. If the systems are optimized, losses associated with HVDC transmission lines are lower than those of HVAC lines: 3% per 1,000 km compared with 7% per 1,000 km for a typical  $\pm 800$  kV line [4]. Losses of a sea HVAC line can reach 60% per 100 km. This statement remains true even when one adds losses associated to converters (about 0.6 % of the transmitted power per station).
- Lower investment cost. A HVDC line costs less for the same transmission capacity even when accounting for the conversion stations that are required at both sides of the lines since producers and customers are normally using AC technologies. Considering both factors (investment costs and losses), HVDC lines are economically feasible for distance of about 600-800 km on land and 50 km overseas [4].

- Lower use of land space. Technically, the HVDC transmission lines have more capacity than the HVAC lines for the same voltage: the maximum capacity of a typical  $\pm 800$  kV HVDC lines is around 6,400 MW whereas the maximum capacity of a HVAC line is only 2,000 MW [4]. In addition, HVDC lines consist of a dipole with a positive and a negative line, while HVAC lines consist of three phases and consequently three lines and larger pylons. However, environmental issues of DC are associated with the converter stations: they include audible noise, visual impact, electromagnetic compatibility, and use of ground or sea return path in monopolar operation.

Other technical advantages of HVDC are [7]:

- Asynchronous connection. Due to stability reasons, DC systems are the only options for connecting two AC networks and for connecting two networks with different frequencies (50 and 60 Hz).
- Controllability. Control of the active power is easy.
- Limit short circuit currents. The DC systems do not contribute to the short circuit current of the interconnected AC system.

■ **Existing infrastructure capacity** - In 2012, HVDC transmission lines globally reached 195 GW of capacity (Table 1) with another 133 GW of capacity planned in about 65 projects [6].

New projects range from 100 MW of capacity to 7000 MW (the Plains and Eastern Clean Line project in the USA). China alone accounts for a large part of the new capacity with several projects of 3000 MW and 6400 MW [6].

The configuration of electric transmission and distribution (T&D) systems vary across regions. For example, the US electric system consists of three independent but synchronized grids linked through low-capacity DC lines: the Eastern Inter connection (73% of sales), the Western Interconnection (19% of sales), and the Electric Reliability Council of Texas (8% of sales) [10]. All together, these three grids represent about 275,000 km of high-voltage (> 200 kV) transmission lines (3,800 km of 765 kV AC lines and more than 4,800 km of 500 kV DC lines) and 9.7 million km of low-voltage distribution lines [10]. There are hundreds of organizations involved in the transmission of bulk power: private utilities own 66% of the transmission system, while federal companies own 14%. Electricity sales and transmission rates are regulated by the U.S. Federal Energy Regulatory Commission (FERC). About 3,200 organizations are involved in electricity distribution and retail to serve about 125 million of residential customers, 17.6 million of commercial customers and 0.8 million of industrial customers [10].

In the European Union, there are four interconnected

**Table 1** – Existing HVDC transmission line capacity in the world [6]

World Regions/ Countries	Power rating (GW)
Africa	7.2
Australia-NZ	4.1
Canada	12.5
Canada-USA	4.1
China	61.3
Europe	21.4
India	22.4
Japan	4.3
Other Asia	4
Russia - Europe	4.5
Saudi Arabia	1.8
South America	21.1
USA	25.7
USA-Mexico	0.2
<b>Total</b>	<b>194.4</b>

HV transmission systems: the Continental Europe, the Nordic Countries, the UK and the Irish systems [5]. However, the Baltic States are still interconnected to the IPS-UPS network based on the Commonwealth of Independent States (CIS). Few transmission lines with non-European countries (Russia, Ukraine, Turkey and North African countries), also allow electricity trade outside the European Union [5]. Since regional or even national electric networks are normally operated by a single company, electricity transport is usually regulated by designated agencies in the EU member states, and transmission activities are usually separated from the retail ones to facilitate the liberalised electricity market [5].

For the transmission segment, Transmission System Operators (TSOs) are responsible for the main high voltage electric networks and provide access to market players following transparent rules and security issues [5]. In 2009, the European Union adopted a new legislation to strengthen the internal energy market by allowing competition among companies, and consequently, to provide the lowest energy prices to consumers. The new legislation also aims at increasing collaboration between member states to develop common security standards and to plan capital investment projects, via a new TSOs association, the European Network for Transmission System Operators for Electricity (ENTSO-E) [5]. Total electricity flow between European countries totalized 411,934 GWh in 2011 as illustrated in Figure 4 [12]. There are more than 4 million distribution transformers.

For the distribution segment, networks are normally low-voltage (< 1 kv) or medium voltage (1-100 kv), as

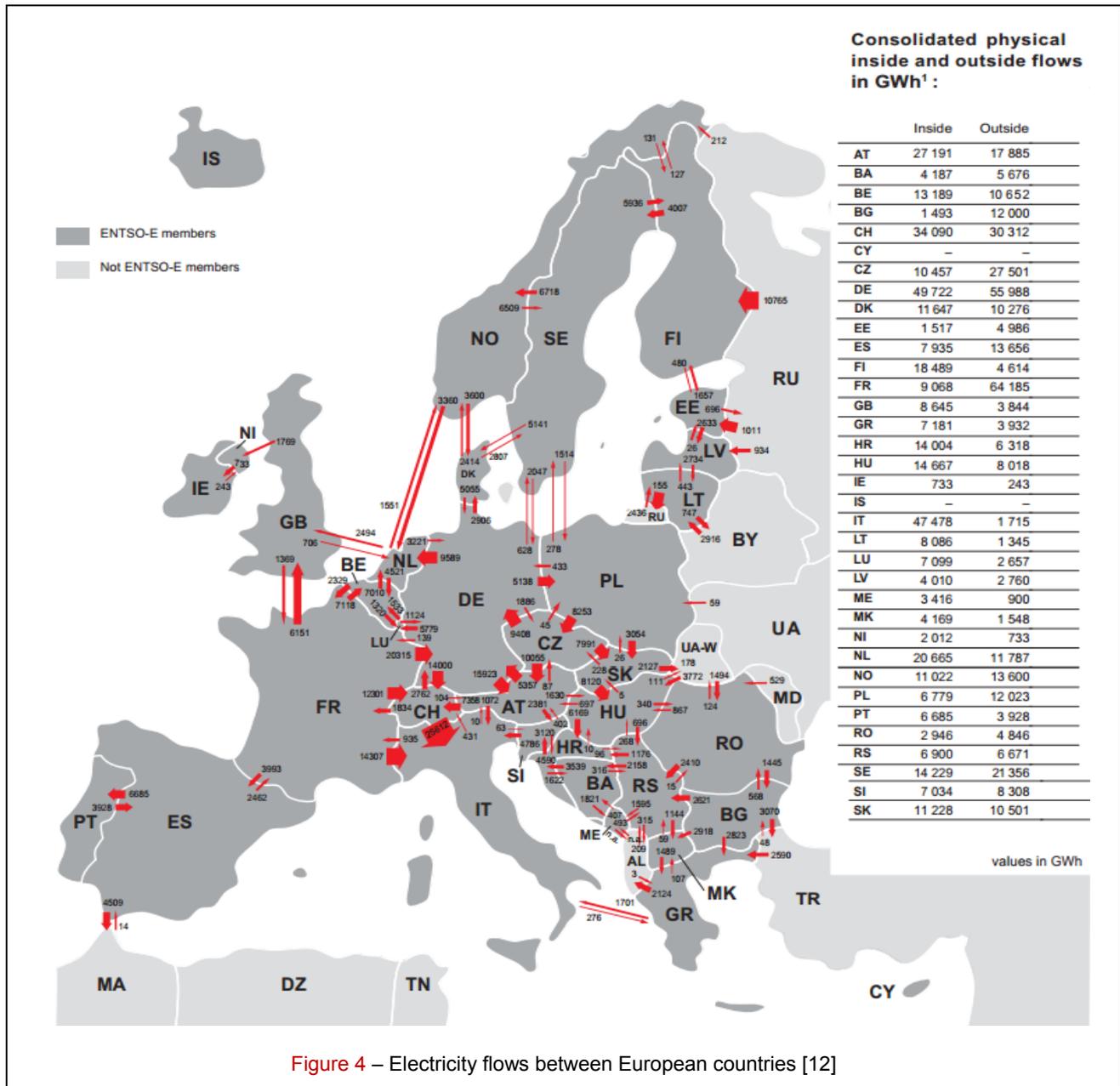


Figure 4 – Electricity flows between European countries [12]

well as local or regional infrastructure in rural areas. In the European Union, there are about 2,400 distribution companies of various sizes [5]. Electricity distribution represents 260 millions of connected consumers providing 2,700 TWh per year through 10 million km of power lines (97% of all power lines in Europe) that are linked to the transmission network by 10,700 interconnection points (see Table 2 for more data by countries). The EURELECTRIC Networks Committee works with the Distribution System Operators (DSOs) based on three working groups for: customers and operation; regulation and policy; and smart grids. Similarly to the TSOs, the DSOs are intended to act as facilitators for market transparency [5].

## PERFORMANCE AND COSTS

■ **Energy Losses** – Electricity transmission and distribution involve energy losses that are measured as the fraction of the transported energy that is lost mainly due to line heating. This fraction represents an important measure of the performance of a transmission and distribution system.

**Transmission systems.** Losses are reduced when power is transmitted at a higher voltage; the fraction of power lost due to resistance is lower. As mentioned, electricity losses are lower in HVDC than in HVAC over long distances: for a ±800 kV line voltage, losses are about 3% per 1,000 km for an HVDC while they are

**Table 2 – Distribution networks by country in Europe as of 2011 [5]**

	No of DSO	Numbers of consumers			Total distrib. power (TWh)	Total distribution power length (km)						No of mid-low transform	No of DSO-TSO interc. points	
		<1kV	1-100kV	>100kV		All	>100kV overhead	>100kV undergr.	1-100kV overhead	1-100kV undergr.	<1kV overhead			<1 kV undergr.
AT	138	5,700,000	150,000	100	61	235,600	9,200	560	29,250	36,300	37,600	122,700	76,800	na
BE	24	5,178,890	64,906	0	55	193,165	0	0	7,021	65,501	52,164	68,480	69,398	544
BG	4	4,909,374	6,123	0	26	153,916	73	41	49,651	14,801	63,533	25,817	48,543	524
CY	1	512,972	646	0	5	22,428	0	0	5,482	3,305	9,206	4,434	14,774	1,800
CZ	3	5,812,727	24,258	134	65	221,441	12,245	13	58,734	12,979	65,764	71,706	3,677	30
DE	880	na	na	na	511	1,772,696	106,869	7,018	122,226	384,445	143,516	1,008,622	461,900	
DK	72	na	na	na	33	171,819	1,364	379	8,629	65,354	3,961	92,132	71,100	
EE		651,000	1,000	0	8	60,000	0	0	20,000	6,000	26,000	8,000	25,000	350
ES		27,682,771	103,630	397	278	695,427	30,363	1,017	203,225	77,620	241,735	141,467	289,671	776
FI		3,305,268	3,761	117	60	382,740	6,438	184	121,153	17,000	148,758	89,208	133,570	567
FR		33,903,690	95,703	0	384	1,293,466	0	0	356,263	251,790	419,060	266,353	751,000	2,240
GR	2	8,184,378	11,347	0	45	229,877	569	208	96,793	9,915	107,837	13,570	156,061	198
HU	6	5,520,991	6,334	138	37	161,954	7,755	118	53,887	12,929	64,039	33,227	59,485	155
IE	1	2,235,681	1,545	6	23	167,528	402	136	87,866	9,924	57,100	12,100	248,588	189
IT	144	31,331,656	90,949	1,018	264	1,105,216	0	0	207,247	135,353	510,301	252,315	426,559	1,728
LT	1	1,570,584	1,205	0	9	123,749	0	0	43,362	10,655	56,848	12,884	36,308	395
LU	6	na	na	na	5	8,477	0	0	1,115	2,044	319	4,999		
LV	11	872,930	926	0	7	93,764	0	0	29,434	5,530	40,640	18,160	28,488	134
NL	11	na	na	na	109	252,634	0	0	na	na	na	na		
PL	184	16,456,000	31,000	300	133	774,141	32,486	185	234,732	70,760	291,671	144,307	250,229	98
PT	13	6,113,839	23,772	0	52	222,627	0	0	66,725	16,531	106,744	32,627	64,458	59
RO		2,633,625	5,602	91	54	89,944	6,332	252	22,645	12,021	28,589	20,106	20,736	25
SE	173	5,300,000	9,000	na	na	528,606	na	na	na	na	69,868	236,151		
SI		820,000	105,275	2	11	63,120	801	10	12,189	4,665	24,655	20,801	16,425	93
SK	3	2,379,672	12,664	82	20	91,353	na	na	na	na	na	na		
UK	7	na	na	na	326	837,156	50,462	24,978	193,102	159,739	70,276	338,599	665,408	637
NO	155	na	na	na	118	128,591	na	na	na	na	na	na	142,651	171

about 7% per 1,000 km for an HVAC line [4]. For HVDC sea cables, losses are about the same but can reach 60% per 100 km for a 750 kV HVAC sea cable.

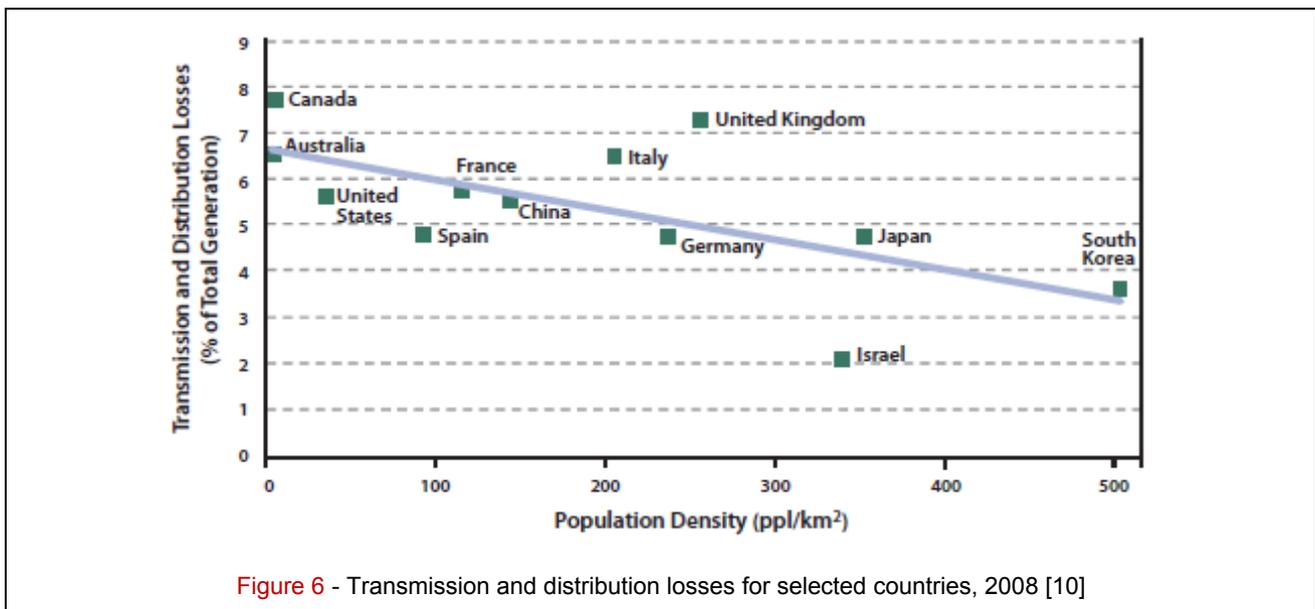
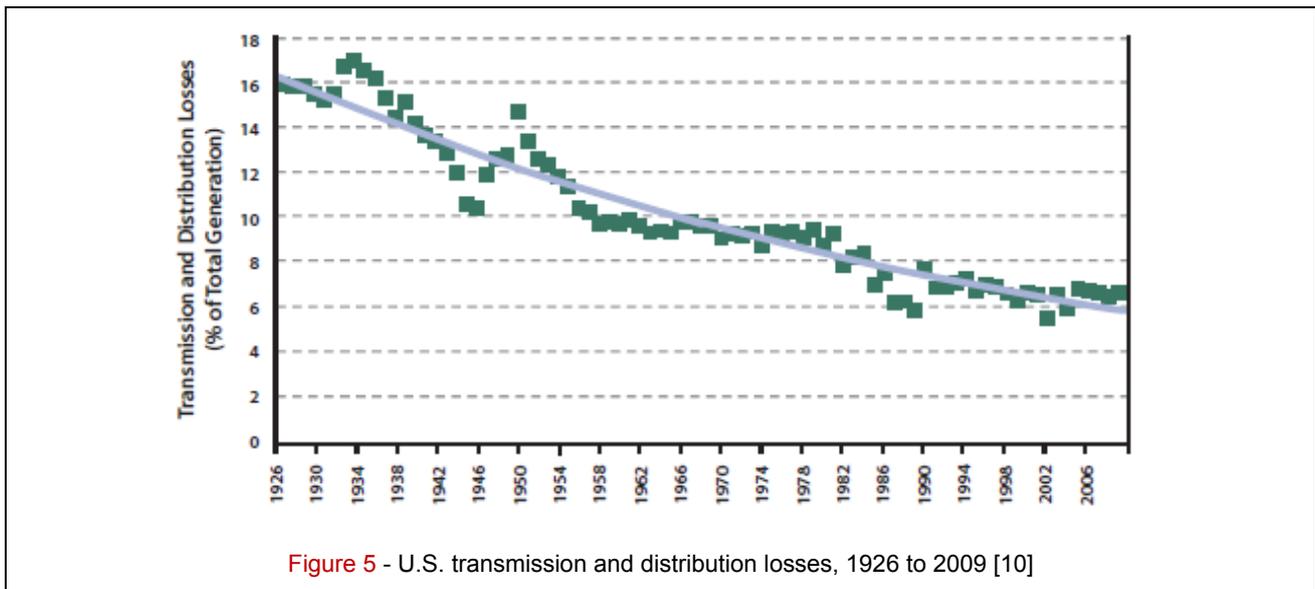
**Distribution systems.** Most of the total transmission and distribution losses occur in the distribution systems. Energy losses have been falling significantly over time. Due to technology advances (e.g. more efficient transformers, higher voltage transmission) in the United States the average energy loss declined from 16% in 1926 to today's 7% (Figure 5). Given as a percent, the current energy loss is similar in all developed countries with similar aging infrastructure (Figure 6) and population density. Specific transmission and distribution losses (% of output) are provided for various world regions in the Table 3.

Regarding the power capacity and associated losses of the different types of lines: for AC, the transmission capacity is a function of reactive power requirements

and security of operation (stability) while for DC, it depends mainly on the thermal constraints of the line [7]. See Table 4 for the transmitted power and relative losses as a function of current distribution network density with a 25 mm diameter conductor.

Transmission and distribution losses are higher with an important increase in the renewable share. A an important study of NREL (National Renewable Energy Laboratory) have shown that losses were about 6.4% in a low demand business-as-usual scenario but were reaching 8.4% to 9.5% in a scenario with 80% of renewable in 2050 [13].

■ **System Reliability** – Reliability is another relevant indicator of performance and it has also improved over time with higher transmission voltage but also other new technology development: detection and isolation of system faults, high-speed reclosing circuit breakers, re-energized automatically in few seconds after a fault, automatic control of lightning strikes with lightning



arrestors [10]. A comparison of minutes of outage per year in several developed countries shows that the US are in line with other countries after taking into account the density of population (Figure 7). In the US, power interruptions occur between 1.5 and 2 times per year with 2 to 8 hours without power. In most European countries, power interruptions occur from less than 1 to almost 3 per year. The reliability varies widely between urban and rural areas according to the existing information (not comprehensive): from 30 seconds to 5 minutes per year in urban areas versus from 9 hours to four days in rural areas [10]. Most interruptions observed by customers occur within distribution systems.

**Transmission systems.** Power systems are configured to face equipment failures, e.g. by disconnecting lines

or generators automatically when problems arise. In addition, operators of power systems maintain a level of generating reserves as well as detailed reacting procedures in case of problems. Due to these measures, most problems occurring in the transmission networks do not have consequences for the costumers. Enhancements in the transmission networks are possible at different stages, see example of existing (in black) and new (in red) technologies in Figure 8.

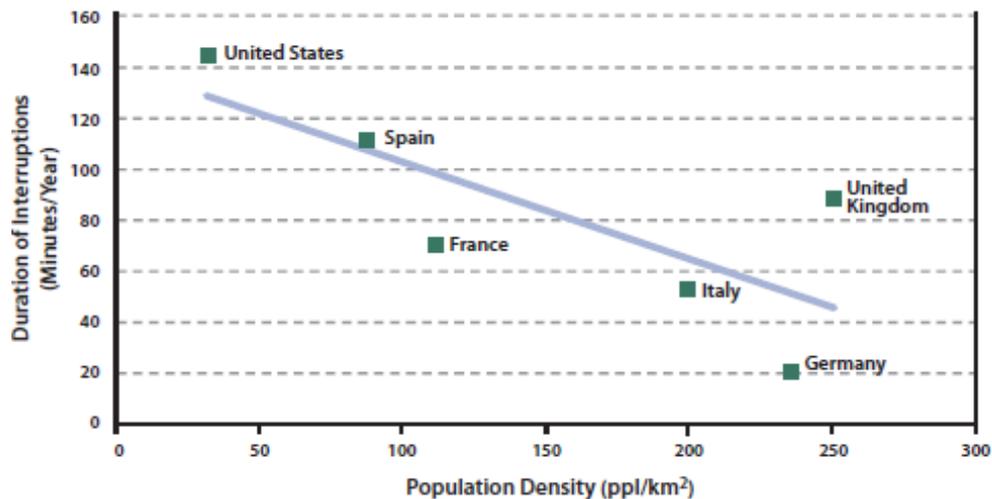
**Transmission Lines.** Generators are used to control voltage at both ends of lines, but with the interconnected characteristic of today's networks (multiple lines and substations), it is impossible to control power on an individual line with no impact the others [10]. Indeed, power can follow several paths creating some congestion problems.

**Table 3 - Electric power transmission and distribution losses (% of output) [8]**

Country Name	2005	2006	2007	2008	2009	2010
Arab World	12.41	11.49	12.37	13.24	13.24	12.41
Caribbean small states	8.58	9.29	7.26	6.06	4.34	11.60
East Asia & Pacific (all income levels)	6.35	6.18	6.01	5.96	5.92	5.89
East Asia & Pacific (developing only)	7.42	7.06	6.78	6.60	6.41	6.46
Euro area	6.09	5.34	5.41	5.34	5.29	5.09
Europe & Central Asia (all income levels)	8.57	8.03	7.95	7.89	7.97	7.68
Europe & Central Asia (developing only)	13.29	13.09	13.05	12.68	13.07	12.43
European Union	6.67	6.08	6.12	6.07	6.08	5.86
Heavily indebted poor countries (HIPC)	17.18	16.41	16.10	16.96	16.27	17.67
Latin America & Caribbean (all income levels)	16.18	16.37	16.24	15.95	16.23	15.31
Latin America & Caribbean (developing only)	16.57	16.80	16.76	16.44	16.63	15.74
Least developed countries: UN classification	14.91	13.35	13.49	13.47	12.31	12.03
Middle East & North Africa (all income levels)	13.04	12.46	13.19	13.48	13.16	12.29
Middle East & North Africa (developing only)	16.13	16.23	17.35	17.65	17.08	15.41
North America	6.37	6.44	6.45	6.17	6.93	6.58
OECD members	6.48	6.34	6.32	6.21	6.60	6.33
Other small states	22.08	21.68	24.84	21.51	23.09	20.45
South Asia	24.93	23.41	21.83	21.24	21.06	20.66
Sub-Saharan Africa (all income levels)	11.26	11.63	10.23	10.57	11.00	11.79
Sub-Saharan Africa (developing only)	11.26	11.63	10.23	10.57	11.00	11.79
World	8.84	8.61	8.47	8.37	8.62	8.31

**Table 4 - Transmitted power and losses for the original double circuit AC lines and the converted DC lines [7]**

	Voltage (kV)	0,7 A/mm <sup>2</sup>		1.0 A/mm <sup>2</sup>		1.4 A/mm <sup>2</sup>	
		Power (MW)	Joule % (per 10Km)	Power (MW)	Joule % (per 10Km)	Power (MW)	Joule % (per 10Km)
AC	33	26	11.0	37	16.1	52	22.6
AC	132	130	3.5	180	4.9	262	7.1
DC	66	89	3.8	127	5.4	178	7.6
DC	264	440	1.2	636	1.7	890	2.4



**Figure 7 - Average Duration of Interruptions for Selected Countries, 2006 [10]**

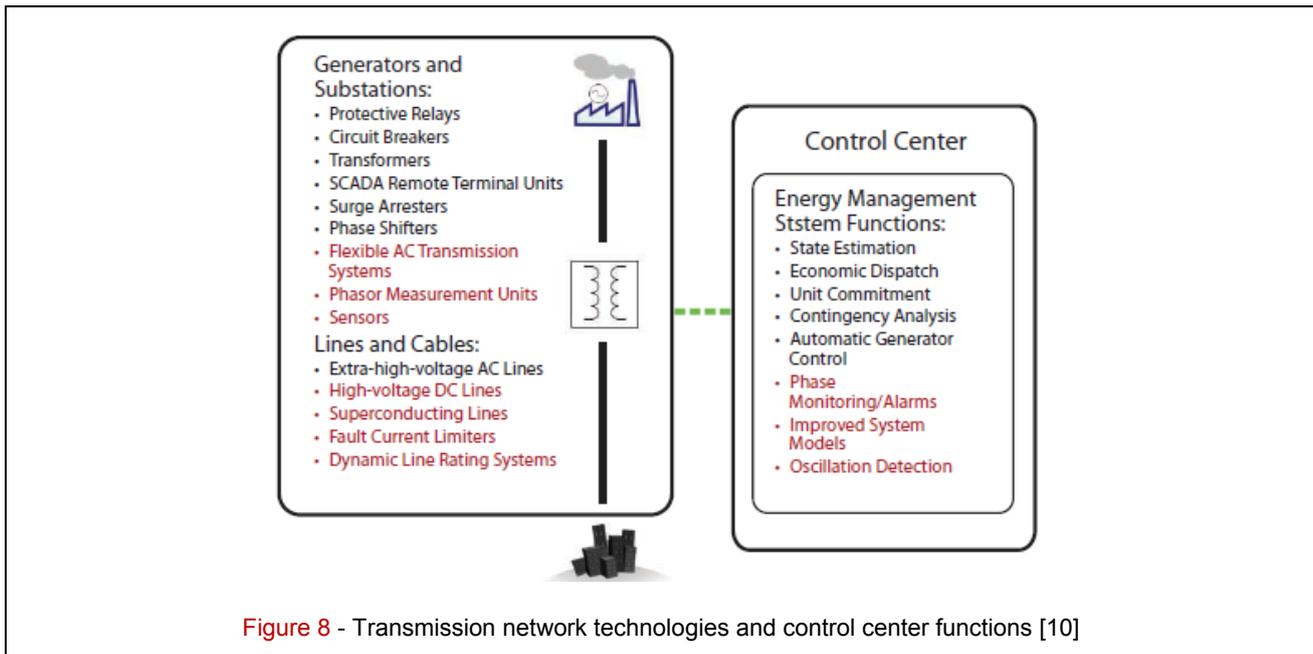


Figure 8 - Transmission network technologies and control center functions [10]

Substations, Voltage Support and System Operation. Substations are used for the interconnection of transmission lines and they are equipped with voltage transformers (e.g. links with the low voltage distribution networks), with protection devices (circuit breakers, and surge arresters) and with data measure and communication equipment used to keep voltage at acceptable levels [10]. Voltage support is becoming critical with the increase of line length and loading. The most common practice relates to the connection of compensating devices to the lines and the control of their voltage contribution following changes in the load. Efficiency and reliability of transmission networks can be further improved with innovative technologies [10]:

- Phasor measurement unit (PMU) devices provide regular and frequent data on the system conditions to system operators in order to allow anticipating failures and contingencies. While these devices are increasingly employed, more work is necessary to optimize the use of data for controlling network.
- Flexible alternating current transmission system (FACTS) devices allow a greater control of voltages and bulk power flows in the systems, and consequently, more power transmission on existing lines with no additional risk of problems.

Control Center. System reliability is also insured through centralized planning at control centers where main operations consist of monitoring, analysis, and control. Control operations involve the calculation of hourly power expected from generating units on a very short term basis (few hours or days) depending on the expected demand (this is called economic dispatch) [10]. Long term planning of the system goes beyond operation planning and is addressed at the utilities and system operator levels.

Reliability of transmission system clearly faces some important challenges, namely for increasing transmission capacity with minimal environmental impact, while incorporating intermittent energy resources [10]. First, the construction of new transmission lines is a long and complex task requiring acquisition of rights-of-way, as well as consolidation of short term with long-term strategic objectives [10]. In addition, some constraints limit the capacity of a transmission line: 1) thermal constraints, since the losses increase the temperature of the line which then stretches between its supports, and 2) stability constraints which represents the system ability of maintaining regular operations after unexpected events (disturbances, failures, etc.) [10]. Thermal constraints are related to the material of the lines, while stability constraints depend on the length of the lines and system conditions. Extensive N-1 contingency analysis is performed in order to define the stability limits [10]. The objective is to make sure that if any single component of the system is broken, the power flows will remain within these limits. There are two main forms of stability limits:

- “Transient stability refers to the ability of a transmission line to accept a transient increase in power flow without exceeding the maximum safe voltage angle between the ends of the line.
- Voltage stability refers to the ability of a power system to maintain acceptable voltage levels across the network after a disturbance. The most common form of voltage instability is a progressive drop in voltages following a disturbance when the automatic controls associated with some loads push generators and transmission equipment beyond their capabilities.” [10].

There is an increasing interest in facing the challenges associated with long distance transmission, namely for the integration of renewable sources which may be distant from economic centers. Long distance transmission is technically feasible, but costly and difficult to implement due to rights-of-way issues. The main two technologies appropriate for this purpose are [10]:

- Extra-high voltage AC (between 242-1000 kV): more power can be transmitted through these lines over longer distance, but supporting infrastructure is also bigger and more expensive (transformers, insulators, etc.). They are cost-effective for large capacity and long distance, but limited by stability constraints.
- High-voltage DC: The length of these lines is not limited by stability constraints. Substation costs are higher as they required more electronic equipment for AC/DC conversion and substation losses are higher (1.5% for AC/DC compared with 0.5% for AC). However, the overall losses are much lower in a DC line than in an AC line, so DC lines are the most appropriate and cost-effective for long distance and point-to-point destination, including for transmission power from renewable sources in remote areas.

Other means are considered for increasing transmission capacity, such as [10]:

- Transmission Overlays: This refers to the superimposition of new high voltage transmission lines over the existing network, but the benefits (less land space to connect more renewables) needs to be balance against the high construction costs of this option.
- Underground and Submarine Cables: Their main advantage relates to their minimal overhead infrastructures and visual impacts, but they are much more expensive and face some constraints: the length for AC lines (dues the high capacitive charging current) and losses for DC lines.
- Superconductors: These are materials with very low resistance below a certain temperature and consequently have a higher capacity, but their deployment is limited by technical difficulties (to maintain the appropriate cooling).
- Phasor Measurements for Increased Transmission Capacity (see above).

**Distribution systems.** While most problems and failures in the transmission network are increasingly well controlled and not observed by costumers, those arising in the distribution networks directly affect them. One reason is related to the physical configuration of distribution lines which are more numerous and vulnerable to uncontrolled events such as storms. In addition, operators of distribution systems use less sophisticated (and less costly) controlling equipment. Consequently, when a tree falls on a distribution line for instance, the failures may be not reported automatically,

and once it is reported, operators need to send a truck repair which involves some additional delays. With the years however, delays have reduced with improvements in problems reporting and location. Using sophisticated controlling devices in distribution systems is less cost-effective than for transmission systems there are much more distribution lines and each of them serves a much lower numbers of costumers.

Improvements and investments in aging distribution networks will be necessary in the next decades, in particular due to emerging challenges such as intermittent renewable penetration. Efficiency and reliability of distribution networks can still be improved with innovative technologies, "...including distribution management system software, more accurate control of voltages, automatic reconfiguration of distribution circuits, and advanced metering infrastructure (AMI) [10]. AMI technologies are particularly relevant as they allow costumers receiving real-time prices based on the real-time supplying cost on one hand and allow operators receiving real-time usage data on the other hand. These technologies will play a critical role as incentives to reduce peak demand, to improve network efficiencies and to lower costs of supplying electricity. There deployment at a large scale will require appropriate legislation. Until now, demand side management through dynamic pricing is starting but at a very slow pace.

■ **Emissions** – Emission factors associated to transmission and distribution losses are normally derived as a percentage of the total electricity generated in a region or a country. According to [11], the portion of electricity consumed during its transmission and distribution vary between 5% in OECD countries and up to 20% in developing countries.

Studies have shown that smart grids have less impact on the environment and can make a significant contribution to energy and carbon savings. For instance, a study from the Pacific Northwest National Laboratory (PNNL) estimates a 12% reduction in electricity consumption and CO<sub>2</sub> emissions in 2030 after a complete implementation of smart grid technologies in the country [9].

■ **Costs and Investment** – Although the cost of HVDC transmission systems vary widely with its design as well as the economic, geographical and environmental conditions, a typical cost structure is the following: Valves (20%), Converter transformers (16%), AC Filters (10%), Control (7%), Other equipment (10%), Civil works, buildings (14%), Engineering (10%), Erection, commissioning (8%), Freight, insurance (5%) [7]. Traditional HVDC systems designated for the transmission of hundreds of megawatts are not economical for less than 20 MW loads. Since the prices go down with the voltage, costs of distribution networks are lower than those of the transmission networks.

Although the exactly values are difficult to define precisely as they depend on many factors, the following values can be used for comparison purposes [7]:

- HVDC system 50 MW, 100kV, Thyristor converter: 500 €/kW
- Light 50 MW, +/-84kV, IGBT converter pair: 150 €/kW
- Transformer 50MVA, 69kV/138kV: 7,5 €/kVA

For a bipolar HVDC line, a cost of 190 k€/km is estimated and converter stations are estimated to 190 M€. For a double AC line, a cost of 190 k€/km (each) is estimated and AC substations (above 600 km) are estimated to 60 M€ [7]. The relation between cost and capacity (MW) is not linear due to the cost of the components that are not dependent on the size of the converter (control and communication system, auxiliary supply) and due to the lower limits on the size required for the land and the building.

**Figure 9** compares cost between HVDC and HVAC systems. A HVDC line costs less for the same transmission capacity than HVAC line. Although, the terminal stations are more expensive because they must perform the conversion from AC to DC and vice versa. The costs of overhead lines and cables, land acquisition/right-of-way costs are lower as well as the operation and maintenance costs. While initial losses are higher, they do not vary with distance like for AC systems, so above a certain distance, the HVDC systems will always give the lowest cost (**Figure 9**). The break-even-distance is smaller for submarine cables (about 50 km) than for overhead lines [7].

In fact, the existing transmission costs represent a different fraction of the total levelized electricity costs for new power plants (**Table 5**): it is significantly higher for intermittent renewable sources.

■ **Investments in transmission system expansion** - Relevant cost information is provided in [13] regarding the future expansion of the transmission network, namely for accommodating a large share of renewable in the electricity mix. Main assumptions used for the various components of the transmission system are listed in **Table 6**.

In general, investments in transmission systems are higher in scenarios with high renewable shares (even if a share of conventional power is replaced by renewable) due to their longer distance from load centers. While the existing transmission capacity in the US is about 93–124 million MW-km, a Low-Demand Baseline scenario requires 3.2 million MW-km of new transmission in 2050. **Table 7** shows new transmission needs for different renewable share scenarios. These figures provide a good indication of the average cost of expanding transmission systems depending on the renewable shares of the electricity mix.

**Table 7** – New transmission investments depending on the renewable shares [13]

Scenarios	New lines (million MW-km)	Interties (MW)	Investments* (billion \$/y)
30% RE	+ 7	+ 6,500	+ \$1.8
60% RE	+ 28	+ 10,500	+ \$4.2
90% RE	+ 60	+ 85,000	+ \$8.3

\* Cost for the new transmission lines, interconnection costs for all plants, etc.

■ **Investments in distribution systems** - Investments in advanced metering infrastructure (AMI), also called smart meters, can improve the performance of distribution systems by combining two-way real time communication between costumers and utilities. There are many benefits associated with AMI for utilities [7]: 1) automated reading reduces labor cost and the costs of owning vehicles for reading operations, 2) more accurate billing improves utilities cash flows, 3) improve costumers support and reduce average call time, 4) more effective management of distribution system assets.

Although AMI can bring significant operational benefits, they do not cover the full investment costs (see **Table 8** for costs and benefits of specific US projects). The average costs of AMI deployment have been varying between 150\$ and 400\$ per meter depending on system conditions, electricity mix, costumers density, labor cost and prior meter investments [7]. Operational savings are more significant in situations where density is low and traditional meter are at the end of their useful life for instance.

## POTENTIAL AND BARRIERS

■ **Global investments in the grid** - In many countries, the existing infrastructure for electricity transmission and distribution is aging and becoming obsolete or overstressed with the increasing penetration of intermittent renewables-based electricity sources.

For instance, a study from the Lawrence Berkeley National Laboratory (LBNL) have estimated the cost of power interruptions in the US at \$79 billion per year (ranging from \$22 billion to \$135 billion in sensitivity analysis) [9].

The International Energy Agency [1] provides some numbers for projected investments in the electricity sector over the 2012-2035 period in their New Policies

Scenario (Reference Scenario): total investment cost for the global generating capacity reaches about \$9.7 trillion dollars, with an additional \$7.2 trillion for transmission and distribution grids (40% to replace existing infrastructure and 60% to build new infrastructure). Depending on the region (**Table 9**), the

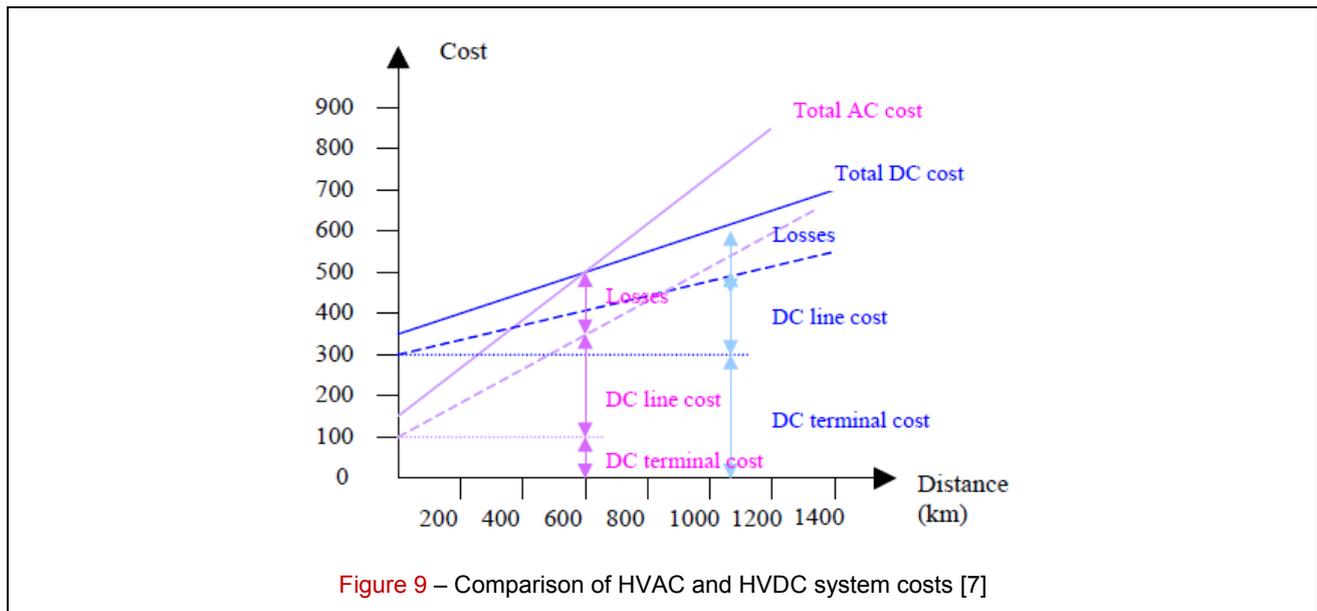


Table 5 - Levelized electricity costs for new power plants, 2020 and 2040 [3]

2011 ¢/kWh	2020				2040			
	Gas combined cycle	Wind	Nuclear	Coal	Gas combined cycle	Wind	Nuclear	Coal
Capital	1.71	6.98	7.73	8.32	1.35	5.88	5.98	6.61
O&M	0.20	1.31	1.16	0.68	0.20	1.31	1.16	0.68
Fuel	4.77	0.00	1.25	3.01	6.71	0.00	1.40	2.89
Transmission	0.12	0.32	0.11	0.11	0.12	0.32	0.11	0.11
Transmission (%)	1.7%	3.7%	1.1%	0.9%	1.4%	4.2%	1.2%	1.1%

Table 6 - Cost related to new transmission lines and interconnections [13]

Transmission and Interconnection	Range	Notes
Long distance transmission lines (\$/MW-km)	746\$-3318\$	High-voltage infrastructure, 500 kV to 765 kV. Include a 25% contingency factor that covers the cost of redundancies in the transmission lines
Substation costs (\$/MW)	\$10,700–\$24,000	Applied to the endpoints of each new transmission lines
Intertie (AC-DC-AC) costs (\$/MW)	\$230,000	Apply when grid expansion spans 2 of the 3 U.S. interconnections
Base grid interconnection costs (\$/MW)	\$110,000	Applied to new generation and utility-scale storage technologies: natural gas, biopower, wind, CSP, and utility-scale PV installations
	\$220,000	Applied to new generation and utility-scale storage technologies: coal, hydropower, geothermal, CAES, and PSH
	\$100,000–\$1,000,000	Applied to new remotely located wind and CSP technologies to account for the distance to the existing transmission system or load centers
Low voltage transmission lines (\$/MW-km)	1491\$-6636\$	

**Table 8 - Operational Benefit–Cost Ratio of AMI projects in the US [10]**

Utility	Year	Meters (millions)	Cost (\$/meter)	Operational benefits (\$/meter)	Operational Benefit/cost ratio	Non-Operational benefits (\$/meter)	Total Benefit/cost ratio
CenterPoint (TX)	2008	2.40	332\$	50\$	0.15		
Delmarva (MD)	2010	0.22	363\$	183\$	0.50	252\$	1.20
Southern California Edison (CA)	2007	5.30	374\$	217\$	0.58	159\$	1.00
Connecticut Light & Power (CT)	2010	1.20	377\$	94\$	0.19	63\$	0.33
Portland General Electric (OR)	2007	0.84	157\$	197\$	1.26	4\$	1.28
Baltimore Gas & Electric (MD)	2009	2.09	253\$	128\$	0.50	478\$	2.40
NY State Electric & Gas (NY)	2007	1.13	322\$	185\$	0.58		
Rochester Gas & Electric (NY)	2007	0.67	250\$	150\$	0.60		
Consolidated Edison (NY)	2007	4.80	149\$	109\$	0.73	55\$	1.10
Pacific Gas & Electric (CA)	2006	9.30	243\$	218\$	0.90	36\$	1.05

**Table 9 - Investment in electricity-supply infrastructure by region and source, 2012-2035 [1]**

(B\$ 2011)	Generation	Transmission	Distribution	Total
OECD	4,139	662	1,986	6,787
Americas	1,569	437	846	2,852
USA	1,266	350	679	2,295
Europe	1,844	175	778	2,797
Asia Oceania	726	50	362	1,138
Japan	409	24	192	625
Non-OECD	5,547	1,187	3,347	10,081
E. Europe/Eurasia	651	134	397	1,182
Russia	397	96	224	717
Asia	3,653	802	2,313	6,768
China	1,939	572	1,200	3,711
India	992	111	517	1,620
Middle East	353	57	166	576
Africa	431	89	225	745
Latin America	458	104	246	808
Brazil	252	69	139	460
World	9,686	1,849	5,332	16,867
European Union	1,728	155	688	2,571

cost for transmission infrastructure varies between 4%-15% of the total cost while it varies between 27%-34% for the distribution infrastructure. The majority of the investments in the transmission and distribution grids are expected in the Non-OECD countries, with China representing 40% of the total, mainly to build new networks. Investments may be required for network expansion, quality improvement and to increase the access for new customers. In OECD regions, investments are rather expected for replacing and refurbishing existing network. Overall, the total length of the global transmission and distribution network worldwide increases by 25 Mkm in 2012 to 93 Mkm in 2035 [1].

■ **Savings from network modernization** - Potential savings resulting from grid modernization are significant with an estimation of 20% in the case of the US grid (more than \$40 billion/year) [9]. Investments of \$165 billion will be required on a 20 year period but the benefit will reach \$638 to \$802 billion [9]. These estimates represent a benefit-to-cost ratio of 4:1. In other studies on the San Diego region and West Virginia, similar ratios (5:1 to 6:1) were attained [9].

The benefits are improved prevention, containment, and restoration of outages, national security, tolerance to natural disasters, public and worker safety, power quality, competitiveness (lower prices), optimization of utilization, remote connection, as well as reduced

equipment failures, energy losses, transmission congestion and environmental impact [9]. Indeed, the Research & Development Multi-Year Program Plan of the US DOE is expected to achieve significant target benefits in 2030, such as a 20% reduction in the national peak demand, a 100% availability to serve all critical loads at all times, a 40% efficiency improvement, a load factor of 70% and a 20% of capacity generated from distributed and renewable energy sources (about 200 GW) [9].

■ **Toward Smart Grids** - The development of future transmission and distribution grids will be influenced by the need to integrate the increasing amount of electricity generated from intermittent renewable sources, and consequently, the need to increase its flexibility (about 3.2% of the total investments) [1,2]. For instance, smart grids use digital communication and control technologies to optimise the operation of the system and to minimize the losses. Another motivation for the development of smart grids technologies is the increasing penetration of electric vehicles on the markets, having a significant impact on the peak load as most drivers will recharge their batteries at night. In this case, smart grids allow electric vehicle charging (grid-to-vehicle) load to be shifted to off peak periods and flattening of the daily load curve. Advanced technologies are also expected to eventually allow using electric vehicles as storage devices feeding back the electricity to the grid when needed (vehicle-to-grid). However, there are still significant technical (low battery discharge rates and storage capacity), economic (lack

of market incentives) and political barriers (lack of regulation and incentives). On the opposite, the development of distributed renewable electricity (such as solar PV in buildings) will have an reducing impact on the investment needs in transmissions networks, although other type of investment may be required to allow consumers providing electricity back to the grid [1].

To face the upcoming challenges, the existing networks need to be extended, upgraded and transformed into so-called *smart grids* (see ETSAP E15 for a complete description of *smart grid* technologies, performance and costs), aimed to meet increasing and changing electricity demand/supply needs. The US Department of Energy (DOE, Office of Electricity Delivery & Energy Reliability) defines the smart grids in comparison with existing grids, based on seven characteristics or functionalities required to meet the future needs (Table 10). The characterization includes standards for electric interconnection, integration, interoperability, test procedures and operating practice. While significant research and technology advances are needed before implementing the smart grids at a large scale, the US DOE identifies R&D priority areas such as [9]:

- 1) home- and distribution-level, with low-power and secure communication;
- 2) distribution system and customer-side sensing;
- 3) grid-to-vehicle and vehicle-to-grid technologies;
- 4) protection and control for high-penetration distributed energy resources, with changing network conditions; and
- 5) operations support tools.

**Table 10** - Comparison of existing grids and smart grids [9]

Characteristics	Existing grids	Smart grids
Enables informed and greater participation by customers	Consumers have limited information and opportunity for participation with power system, unless under direct utility control	Informed, involved, and active consumers – demand response and distributed energy resources
Accommodates all generation and storage options	Dominated by central generation – many obstacles exist for distributed energy resources interconnection and operation	Many distributed energy resources with plug-and-play convenience; distributed generation with local voltage regulation capabilities to support high penetration on distribution systems; responsive load to enhance grid reliability, enabling high penetration of renewables; frequency- controlled loads to provide spinning reserve.
Enables new products, services, and markets	Limited wholesale markets, not well integrated – limited opportunities for consumers	Mature, well-integrated wholesale markets; growth of new electricity markets for consumers; interoperability of products.
Provides power quality for the range of needs in the 21st century	Focus on outages and primarily manual restoration – slow response to power quality issues, addressed case-by-case	Power quality is a priority with a variety of quality/price options – rapid resolution of issues
Optimizes assets and operates efficiently	Limited integration of operational data with asset management – business process silos limit sharing	Greatly expanded data acquisition of grid parameters – focus on prevention, minimizing impact to consumers
Addresses disturbances – automated prevention, containment, and restoration	Responds to prevent further damage – focus is on protecting assets following a fault	Automatically detects and responds to problems – focus on prevention, minimizing impact to consumers, and automated restoration
Operates resiliently against physical and cyber-attacks and natural disasters	Vulnerable to inadvertent mistakes, equipment failures, malicious acts of terror and natural disasters	Resilient to inadvertent and deliberate attacks and natural disasters with rapid coping and restoration capabilities

**Table 11– Summary Table: Key Data and Figures for Electricity Transmission and Distribution**

Technical Performance	Typical current international values and ranges	
Technology variants	Transmission Systems	Distribution Systems
Losses, %	For a ±800 kV line voltage, losses are about 3% per 1,000 km for an HVDC and 7% per 1,000 km for an HVAC line (60% per 100 km for a 750 kV HVAC sea cable). Between 0.2% and 0.6% are occurring at each converter station	Most of the total T&D losses assumed to be in the distribution systems. In the US: from 16% in 1926 to 7% in 2012. In developed countries: 5.1% to 7.7% in 2010 In developing countries: 11.6% to 20.7% in 2010  Higher with an important penetration of renewable: from 6.4% in a low demand scenario for the US to 8.4%-9.5% with 80% of renewable in 2050.
Losses, % by type of AC/DC lines	AC 33kV: 26 MW (11 % per 10 km), 37 MW (16% per 10 km), 52 MW (22.6% per 10 km) AC 132kV: 130 MW (3.5 % per 10 km), 180 MW (4.9% per 10 km), 262 MW (7.1% per 10 km) DC 66kV: 89 MW (3.8 % per 10 km), 127 MW (5.4% per 10 km), 178 MW (7.6% per 10 km) AC 264kV: 440 MW (1.2 % per 10 km), 636 MW (1.7% per 10 km), 890 MW (2.4% per 10 km)	
Reliability (power interruptions)	Most interruptions occur within distribution systems. In the US: 1.5 to 2 times per year (for 2 to 8 hours). In most European countries: from less than 1 to almost 3 per year. (for 30 seconds to 5 minutes per year in urban areas versus from 9 hours to four days in rural areas).	
Typical size (capacity), kV and MW	Maximum capacity of a typical ±800 kV HVDC lines: 6,400 MW Maximum capacity of a typical ±800 kV HVAC line: 2,000 MW	
Total cumulative capacity, GW	HVDC transmission lines globally reached 195 GW of capacity	
Additional capacity, GW	133 GW of new capacity planned in about 65 projects New projects range from 100 MW of capacity to 7000 MW China counts several projects of 3000 MW and 6400 MW.	
CO <sub>2</sub> emissions, gCO <sub>2eq</sub> /kWh	Emission factors associated to T&D losses are estimated as a % of the total electricity generated vary between 5% in OECD countries and up to 20% in developing countries.	

Costs	Typical current international values and ranges (200XX US\$, 1€= 1.3 US\$)	
by technology variant	Transmission Systems	Distribution Systems
Investment cost 1, k€/km	190 k€/km for a bipolar HVDC line and 190 M€ for converter stations, 190 k€/km for a double AC line (each) and 60 M€ for AC substations (above 600 km)	
Invest cost 2, \$/MW-km or \$/MW	Long distance transmission lines : 746-3318 \$/MW-km Substation costs: 10,700–24,000 \$/MW Intertie (AC-DC-AC) costs: 230,000 \$/MW	Lower voltage transmission lines : 1491- 6636 \$/MW-km 150\$ and 400\$ per smart meter
Investments costs of T&D as a % of total electricity delivery costs	4%-15% of the total cost	27%-34% of the total cost
Typical cost breakdown % - Technologies within the T&D systems	Valves (20%), Converter transformers (16%), AC Filters (10%), Control (7%), Other equipment (10%), Civil works, buildings (14%), Engineering (10%), Erection, commissioning (8%), Freight, insurance (5%)	
Typical cost breakdown % - Transmission share in the levelized electricity costs for new power plants in 2020 and 2040	Gas combined cycle (1.7% - 1.4%), Nuclear (1.1% - 1.2%), Coal (0.9% - 1.1%), Wind (3.7% - 4.2%).	

Data Projections	Typical current international values and ranges	
Effic., %, 2010-2020 (2030-)	Most improvement are expected in developing regions with important losses in 2010 (up to 20%). Losses in developed region can currently be as low as 6%	
Inv.cost, US\$ 2012-2035	Investments in the electricity sector: \$9.7 trillion \$ Investments for T&D grids: + \$7.2 trillion (40% to replace existing infrastructure and 60% to build new infrastructure).	
Length of global T&D systems	From 25 Mkm in 2012 to 93 Mkm in 2035.	
Savings from modernization	Savings of \$40 billion/year Benefit-to-cost ratio of between 4:1 and 6:1 ratios.	

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