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COVER NOTE

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REPORT FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS

JRC technical report on "Assessment of the potential for energy efficiency in electricity generation, transmission and storage"

{COM(2023) 1 final}

Contents

5 Conclusions

The present document discusses some technologies in the field of power generation, management and transmission of electrical energy in terms of efficiency, and identifies among them the most promising sectors for energy saving at the EU level.

Electricity generation looks like the sector where efficiency improvement can result in a significant saving of primary energy. This is due to the fact that efficiency in traditional thermal generation has values in the range 35-64 %, which is very low compared to efficiency in HV transmission (about 98 %) and storage (from 50 to 95 %).

Therefore, **thermal generation presents the highest saving margins** compared to HVDC and storage. Among different technologies, and considering the decarbonisation policies, the substitution of older and less efficient technologies (efficiency of 40 % or so) with CCGT would result in a significantly lower consumption of primary energy, as latest CCGT are claimed to reach an efficiency of 64 %. For example, a simplified analysis carried out for an ideal case of complete substitution of coal electricity generation by CCGT (considering data of 2018) shows that it would make it possible to save about 378 TWh/year. Of course, other considerations should be done in order to guarantee all necessary flexibility options to make it possible to run the power system in security conditions.

As for **storage** options, many technologies are available, with completely different features and uses. Therefore, their efficiencies cannot be simply compared, as fields of applications of various technologies are different. Some storage systems are more oriented to energy applications, some to power applications; some can store large amount of energy, some can provide small amount of energy but in very short time. Hence, for example, one cannot decide to substitute a PHS with a Supercapacitor in order to increase the overall efficiency.

However, this is not an issue, as it should be kept in mind that the goal of storage is not to save primary energy *directly*, but to make it possible the best integration of RES, thus substituting electricity from fossil fuels with RES based electricity, improving at the same time efficiency of residual thermal plants by flattening their load diagram, obtaining a significant *indirect* saving of primary. According to estimates by ENTSOE, the not curtailed RES energy could be reduced in 2030 by 10.6 TWh/year thanks to storage employment.

As for **HVDC transmission systems**, it is worth noticing that transmission efficiency of traditional HVAC systems is today about 98 %, thanks to the extremely high rated voltage of the European transmission system (400 kV). Therefore, there is not much room for further efficiency improvements, unless higher voltages are adopted, for both DC and AC solutions, that would be not justified economically, however. At equal voltage levels, HVDC systems are not an option to increase efficiency compared to HVAC transmission systems. They are a solution when the HVAC transmission is not viable, i.e., in case of very long transmission lines (overhead lines longer that about 800 km, cable lines longer than 100 km, interconnections of not synchronous areas, etc.). Moreover, they should be considered as a tool to make the transmission system more flexible, in order to – again – better integrate RES generation, thus saving *indirectly* primary energy. The typical example is the HVDC interconnection of large offshore wind farms, which is sometimes the only feasible option to make it possible their connection to the bulk power system.

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List of abbreviations and definitions

AC	Alternate Current
ALK	ALKaline electrolyser
BESS	Battery Energy Storage Systems
CAES	Compressed Air Energy Systems
CCGT	Combined Cycle Gas Turbine
DC	Direct Current
DCCB	Direct Current Circuit Breaker
DOD	Depth Of Discharge
EHV	Extremely High Voltages
ENTSO-E	European Network of Transmission System Operators for Electricity
FACTS	Flexible AC Transmission Systems
GT	Gas Turbine
HP	High Pressure
HRSG	Heat Recovery Steam Generator
HV	High Voltage
HVAC	High Voltage Alternate Current
HVDC	High Voltage Direct Current
IGBT	Insulated Gate Bipolar Transistor
IGCC	Integrated Gasification Combined Cycle
LAES	Liquid Air Energy Systems
LCC	Line Commutated Converter
LP	Low Pressure
MMC	Modular Multilevel Converter
MP	Medium Pressure
OCGT	Open Cycle Gas Turbine
P2H	Power to Hydrogen
PEM	Proton Exchange Membrane
PHS	Pumped Hydro Storage

RES	Renewable Energy System
ROW	Right-Of-Way
RTE	Round Trip Efficiency
SMES	Super Magnetic Energy System
SOC	State of Charge
STATCOM	STATic synchronous COMpensator
SVC	Static Var Compensator
TSO	Transmission System Operator
TYNDP	Ten-Year Network Development Plan
VLA	Vented Lead-Acid
VRLA	Valve-Regulated Lead-Acid
VSC	Voltage Source Converter

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APPENDIX I - Coal

Table A.1 EU Annual Production of Electricity from Coal [TWh] (Source Bp Stats review 2020)

Year	EU Annual Production of Electricity from Coal [TWh]	EU Total Annual Electricity Production [TWh]	Coal Production as a Proportion of Annual EU Electricity Generation [%]
1985	969,7	2321,0	41,8
1986	994,9	2377,1	41,9
1987	1010,0	2450,4	41,2
1988	998,7	2507,2	39,8
1989	1022,5	2564,0	39,9
1990	1040,2	2594,9	40,1
1991	1042,8	2640,8	39,5
1992	996,3	2624,6	38,0
1993	951,7	2627,2	36,2
1994	955,8	2665,8	35,9
1995	965,2	2747,0	35,1
1996	976,6	2842,4	34,4
1997	926,2	2858,3	32,4
1998	931,4	2925,1	31,8
1999	896,3	2955,4	30,3
2000	948,5	3037,7	31,2
2001	960,7	3119,7	30,8
2002	967,7	3142,9	30,8
2003	1025,5	3237,2	31,7
2004	1005,1	3305,6	30,4
2005	981,1	3327,3	29,5
2006	1003,8	3371,2	29,8
2007	1006,6	3384,3	29,7
2008	919,2	3388,7	27,1
2009	836,3	3224,4	25,9
2010	846,1	3364,7	25,1
2011	869,7	3299,2	26,4
2012	920,1	3295,4	27,9
2013	892,8	3269,6	27,3
2014	825,7	3188,4	25,9
2015	811,1	3236,6	25,1
2016	721,2	3259,4	22,1
2017	694,2	3290,0	21,1
2018	643,6	3270,1	19,7

2019	488,4	3215,3	15,2

Table A.2. Classification of pulverized coal combustion (PCC) power plants in terms of steam parameters i.e., steam temperature and pressure and materials necessary in high temperature components [1.3, 1.7]

Technology	Superheater temperature and pressure	Material in high temperature components	η Efficiency LHV net Hard coal [%]	Coal Consumption [gCOAL/kWh]
SUBCRITICAL SB	≤ 540°C < 22,1 MPa	Low alloy CMn and Mo ferritic steels	**<35**	≥380
SUPERCRITICAL SC	540°C÷580°C 22,1÷25 MPa	Low alloy CrMo steels and 9–12% Cr martensitic steel	**35÷40**	380÷340
ULTRASUPERCRITICAL USC	580°C÷620°C 22÷25 MPa	Improved 9–12% Cr martensitic steels and austenitic steels	**40÷45**	340÷320
ADVANCED ULTRASUPERCRITICAL A-USC (ONLY UNDER STUDY)	700°C÷720°C 25÷35 MPa	Advanced 10–12% Cr steels and nickel alloys	**45÷52**	320÷290

APPENDIX II - Gas

Table A.3. Natural gas production as a proportion of annual global electricity generation (Source: Bp Stats review 2020)

Year	Annual Production of Electricity from Natural Gas [TWh]	Total Global Annual Electricity Production [TWh]	Natural Gas Production as a Proportion of Annual Global Electricity Generation [%]
1973	740	6117	12,1
2004	3420	17 450	19,6
2005	3623	18 239	19,7
2006	3805	18 930	20,1
2007	4132	19 771	20,9
2008	4299	20 181	21,3
2009	4292	20 055	21,4
2010	4758	21 431	22,2
2011	4846	22 126	21,9
2012	5100	22 668	22,5
2013	5084	23 434	21,7
2014	5241	24 030	21,8
2015	5588	24 266	23,0
2016	5824	24 923	23,4
2017	5926	25 643	23,1
2018	6083	26 653	22,8
2019	6298	27 005	23,3

Table A.4. EU Annual Production of Electricity from Natural Gas [TWh] (Source Bp Stats review 2020)

Year	EU Annual Production of Electricity from Natural Gas [TWh]	EU Total Annual Electricity Production [TWh]	Natural Gas Production as a Proportion of Annual EU Electricity Generation [%]
1985	169,0	2321,0	7,28
1986	171,3	2377,1	7,21
1987	181,4	2450,4	7,40
1988	181,3	2507,2	7,23
1989	198,1	2564,0	7,73
1990	190,1	2594,9	7,33
1991	190,7	2640,8	7,22
1992	186,7	2624,6	7,11
1993	213,5	2627,2	8,13
1994	242,1	2665,8	9,08
1995	267,8	2747,0	9,75
1996	312,3	2842,4	10,99
1997	360,2	2858,3	12,60
1998	390,5	2925,1	13,35
1999	453,7	2955,4	15,35
2000	477,9	3037,7	15,73
2001	494,5	3119,7	15,85

Year	EU Annual Production of Electricity from Natural Gas [TWh]	EU Total Annual Electricity Production [TWh]	Natural Gas Production as a Proportion of Annual EU Electricity Generation [%]
2002	527,6	3142,9	16,79
2003	570,5	3237,2	17,62
2004	617,6	3305,6	18,68
2005	668,5	3327,3	20,09
2006	683,1	3371,2	20,26
2007	738,8	3384,3	21,83
2008	790,7	3388,7	23,33
2009	733,1	3224,4	22,74
2010	764,8	3364,7	22,73
2011	701,3	3299,2	21,26
2012	580,6	3295,4	17,62
2013	507,4	3269,6	15,52
2014	456,0	3188,4	14,30
2015	495,3	3236,6	15,30
2016	608,1	3259,4	18,66
2017	660,7	3290,0	20,08
2018	621,2	3270,1	19,00
2019	692,2	3215,3	21,53

Overview of GT manufacturers

1. General Electric (including former Alstom, acquired at the end of 2015);
2. Siemens (formerly Siemens–Westinghouse, formerly separate companies, i.e., Kraftwerk Union (KWU) Siemens Power Generation and Westinghouse Electric Corporation);
3. Mitsubishi Hitachi Power Systems (MHPS, formerly Mitsubishi Heavy Industries, MHI);
4. Ansaldo Energia.

Ratings and efficiencies of GTs are annually reported in two Journals i.e.:

- Gas Turbine World (GTW), http://www.gasturbineworld.com;
- Turbomachinery International (TMI), https://www.turbomachinerymag.com.

Table A.5 reports all the heavy-duty gas turbine up to 2020 with power ratings greater than 100 MW.

In order to understand the symbols in Table A.5, the following classification is used. In fact, heavy-duty industrial gas turbines are subdivided in accordance with their nominal **TIT** (as already explained, the hot gas temperature at the exit of the combustion section just before entry into the turbine). There are four major classes:

- E class with nominal TIT of 1 300°C;
- F class with nominal TIT of 1 400°C;

— H class with nominal TIT of 1 500°C;

— J class with nominal TIT of 1 600°C.

Table A.5 2018-2018 GT world simple cycle specifications [1.18]: power ratings > 100 MW

MODEL	YEAR OF INTRODUCTION	ISO BASE LOAD RATING [MW]	η **[%]**	NOTES
ANSALDO ENERGIA				
AE94.2	1981	185	**36,2**	
AE94.2K	1981	170	**36,5**	LOW LHV FUEL
AE 94.3A	1995	325	**40,1**	
GT26	2011	345	**41,0**	
GT36-S6	2016	340	**41,0**	
GT36-S5	2016	500	**41,5**	
GENERAL ELECTRIC				
9E.03	1992	132	**34,6**	
9E.04	2014	145	**37,0**	
9F.03	1996	265	**37,8**	
9F.04	2015	288	**38,7**	
9F.05	2003	314	**38,2**	
9HA.01	2011	446	**43,1**	
9HA.02	2014	557	**44,0**	Calculated TIT =1670 °C
MITSUBISHI HITACHI POWER SYSTEMS (50 Hz)				
H-100	2013	118,08	**38,3**	
M701DA	1981	144,09	**34,8**	
M701G	1997	334	**39,5**	
M701F	1992	385	**41,9**	

MODEL	YEAR OF INTRODUCTION	ISO BASE LOAD RATING [MW]	η **[%]**	NOTES
M701J	2014	478	**42,3**	
M701JAC	2015	493	**42,9**	
SIEMENS ENERGY (50 Hz)				
SGT5-2000E	1981	187	**36,2**	
SGT5-4000F	1995	329	**41,0**	
SGT5-8000H	2008	450	**41,0**	
SGT5-8000HL	2017	465	**42,0**	
SGT5-9000HL	2017	564	**42,5**	
PW POWER SYSTEMS (50 Hz)				
FT4000SWIFTPAC120	2012	140,376	**40,9**	
ETHOSENERGY				
TG50D5U	2007	144,5	**34,6**	
BHARAT HEAVY ELECTRICALS				
MS9001E(9E.03)	2012	130,4	**34,4**	
MS9001FB(9F.03)	1996	250,2	**37,5**	
MS9001FB (9E.05)	2004	297,0	**38,9**	

From Table A.5, state of the art in the largest and most efficient heavy-duty GTs can be summarized as follows:

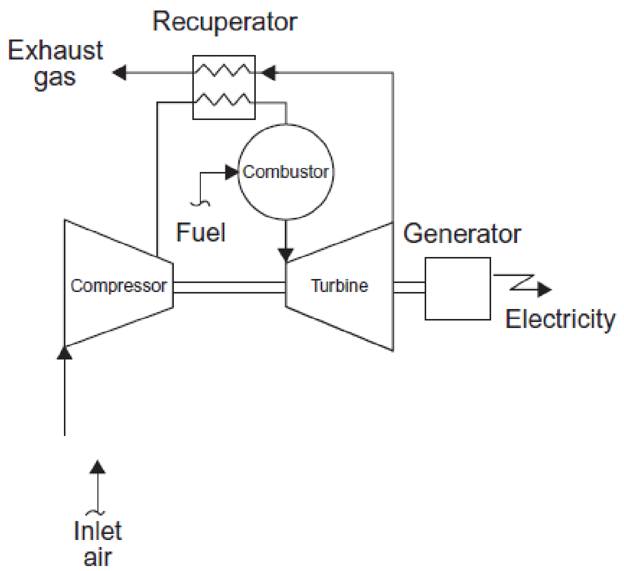
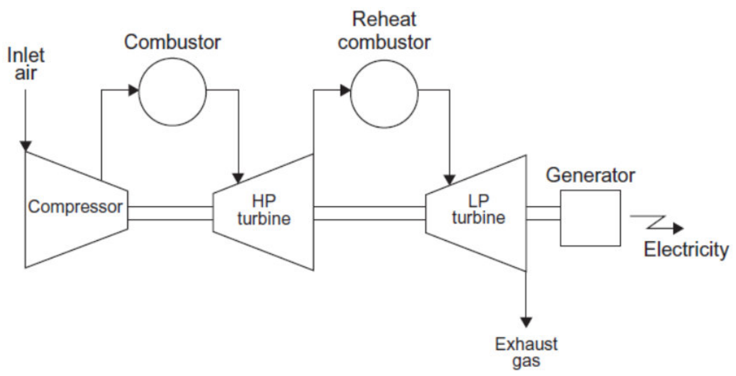
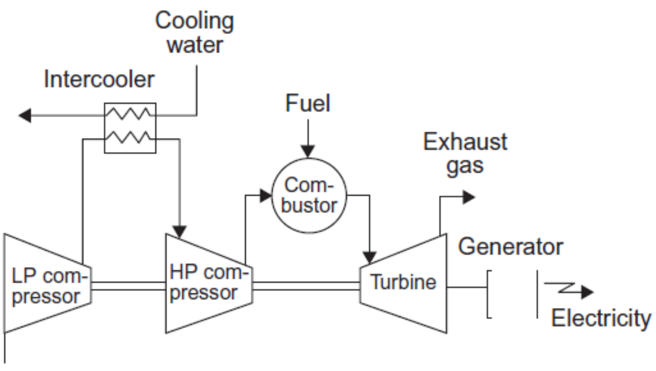
- Outputs of 500 MWe;
- TITs of 1700°C;
- Cycle pressure ratios above 20:1 and as high as 25:1;
- Maximum Efficiency of 44%.

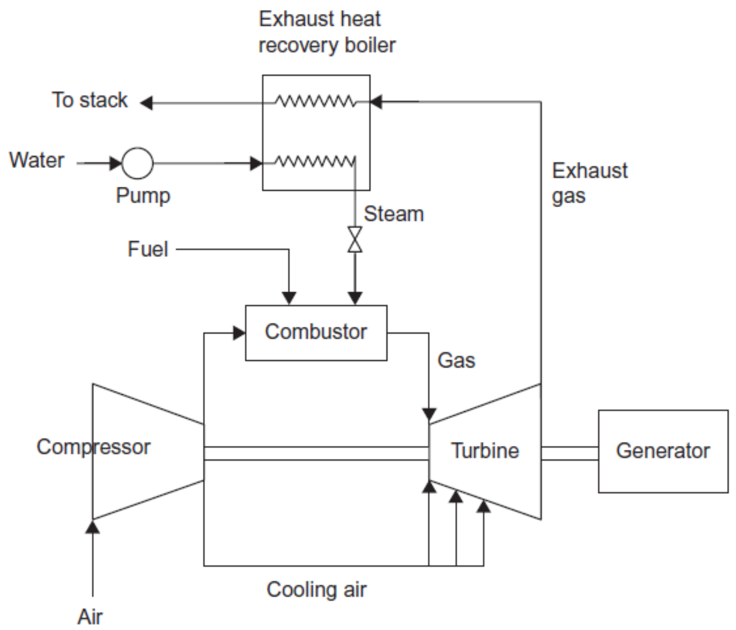
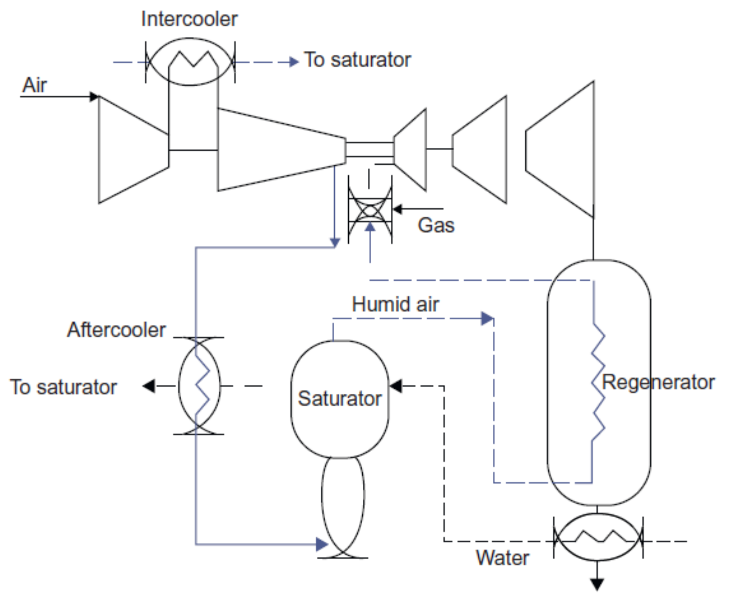
Advanced gas turbine

Many modifications can be implemented to the simple cycle of a GT in order to improve its overall efficiency. Table A.6 sums up the different possibilities and the achievable efficiencies [101].

Table A.6 Modifications in GT cycle in order to increase efficiency

Typology of modification	Efficiency	Scheme

Typology of modification	Efficiency	Scheme
Recuperation	40,2	
Reheating	Alstom	
Intercooling	46 % GE LMS 100	

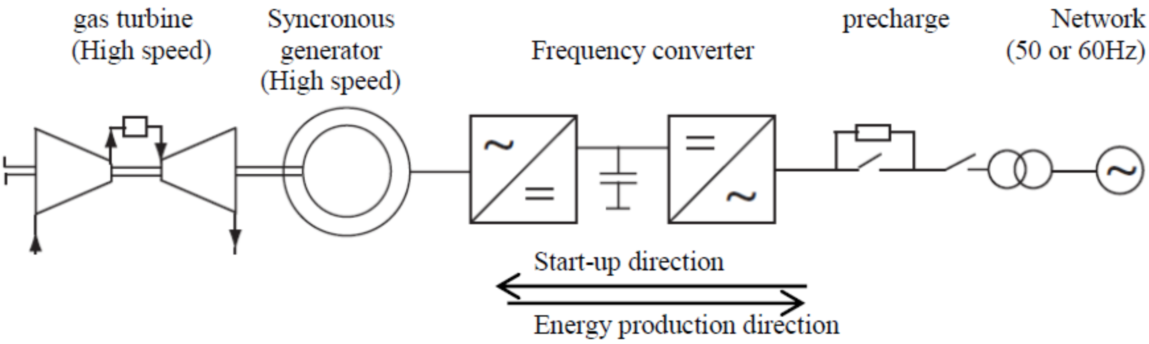
Typology of modification	Efficiency	Scheme
Mass Injection	The net result is an increase in efficiency compared to the same turbine without steam injection of 2% - 4%.	
Humid **A**ir **T**urbine (**HAT**) cycle	55 %	

Some authors propose to substitute the mechanical gearbox that links the turbine shaft with the synchronous generator: this gearbox reduces the rotational speed by maintaining the rpm necessary to the synchronous generator (depending on the polar couples). The gearbox could be substituted by a flexible electronic solution, which offers the ability to operate with very high power and increases turbine efficiency by using variable speed[102].

The paper does not give the overall efficiency gain, but it only specifies that the frequency converter efficiency is 99,5 % whereas the typical efficiency of a gearbox is 98,5 %.

Figure B1 offers a suggestion of the electrical power generation system by using frequency converter.

Figure B1. Scheme of the electrical power generation system using frequency converter



APPENDIX III – Storage

Table C.1 Overview of the life of electric energy storage systems

Technology	Average Life [years]	Discharge time
PHS	50	1 hour-more than 24 hours
CAES	20-40	1 hour-more than 24 hours
FES	15-20	seconds - 15 min
Pb-A	15-30	Typical rated discharge time: 5 h
Li-ion	5-16	Typical rated discharge time: 1 h
NiCd	10-15	10 minutes-5 hours
NaS	15-20	Typical rated discharge time: 8 h
$NaNiCl_2$	15	Typical rated discharge time: 3 h
ULTRACAP	10-15	milliseconds-hours

APPENDIX IV – HVDC Technologies

Table D.1. is adapted and updated from Cigré TB # 432 "Voltage Source Converter (VSC) HVDC for Power Transmission – Economic Aspects and Comparison with other AC and DC Technologies" [103] Moreover, table D.1 gives an immediate comparison between the two different HVDC technologies in terms of power transmission.

Table D.1 Bulk Power transmission by means of HVDC-LCC and HVDC-VSC (updated from [103])

Power Range	HVDC- LCC	HVDC- VSC
7500 MW-12000 MW	UHVDC Bulk (Bipole DC 1100 kV)	
5000 MW- 7500 MW	UHVDC Bulk (Bipole DC 800 kV)	-
2500 MW-5000 MW	UHVDC Bulk (Bipole DC 800 kV)	-
1800 MW-3500 MW	HVDC Classic (Bipole DC 500 kV)	Bulk power VSC HVDC (Overhead line)
700 MW-2000 MW	HVDC Classic (Bipole DC 400kV-500kV)	High power VSC HVDC
300 MW-800 MW	HVDC Classic (Monopole DC 300kV-500kV)	Medium power VSC HVDC
< 300 MW	HVDC Classic (Monopole DC< 300kV)	Low power VSC HVDC

The main characteristics of HVDC-LCC are summed up in Table D.2. The table is taken from [103] but it has been updated and adapted.

Table D.2 State of the art of HVDC – LCC (updated from [103])

Power Transmission	**Overhead lines**	**Insulated Cables**
Maximum voltage level	**1100 kV DC**	**500 kV DC (600 kV_{dc} with PPL MI)**
Maximum power rating	**<12000 MW**	
Maximum transmission distance	**Unlimited**	
Footprint	**200 x 120 x 20 m (600 MW)**	
Active power flow control	**Continuous, min. 10% load**	
Reactive power demand	**50%-60% of converter power rating** **Compensated by breaker switched ac harmonic filters and reactive power banks**	
AC Voltage control	**Slow, transformer tap change**	
Power Reversal	**DC voltage reversal**	
Necessary filter equipment	**High demand**	
Grid connection requirements	**SCR> 2 x power rating**	
Black start / island supply	**Not inherently available**	
Typical Power Loss in the two converter stations at full power	**1,4%**	

Table D.3 sums up the main characteristics of HVDC-VSC.

Table D.3 State of the art of HVDC – VSC (updated from [103])

Power Transmission	**Overhead lines**	**Insulated Cables**
Maximum voltage level	**≤ 640 kV**	**≤ 600 kV**
Maximum power rating	**< 1600 MW**	
Maximum transmission distance	**Theoretically unlimited (voltage drop over line)**	
Space requirements (examples)	**120 x 50 x 11 m (550 MW); 48 x 25 x 27 m (500 MW) [w x l x h]**	
Active power flow control	**Fast continuous**	
Reactive power demand	**Can provide or consume controlled reactive power as required**	
AC Voltage control	**Continuous, full response in < 100 ms**	
Power Reversal	**DC current reversal**	
Necessary filter equipment	**Low demand (PWM); Not necessary with other topologies**	
Grid connection requirements	**Can supply power to a passive network**	
Black start / island supply	**Black-start capability and island supply requires an aux. power system to initially energize the cooling system (e.g.,by means of a diesel generator)**	

HVDC-LCC converter station power losses

Table D.4 Converter station power losses due to each component in HVDC-LCC

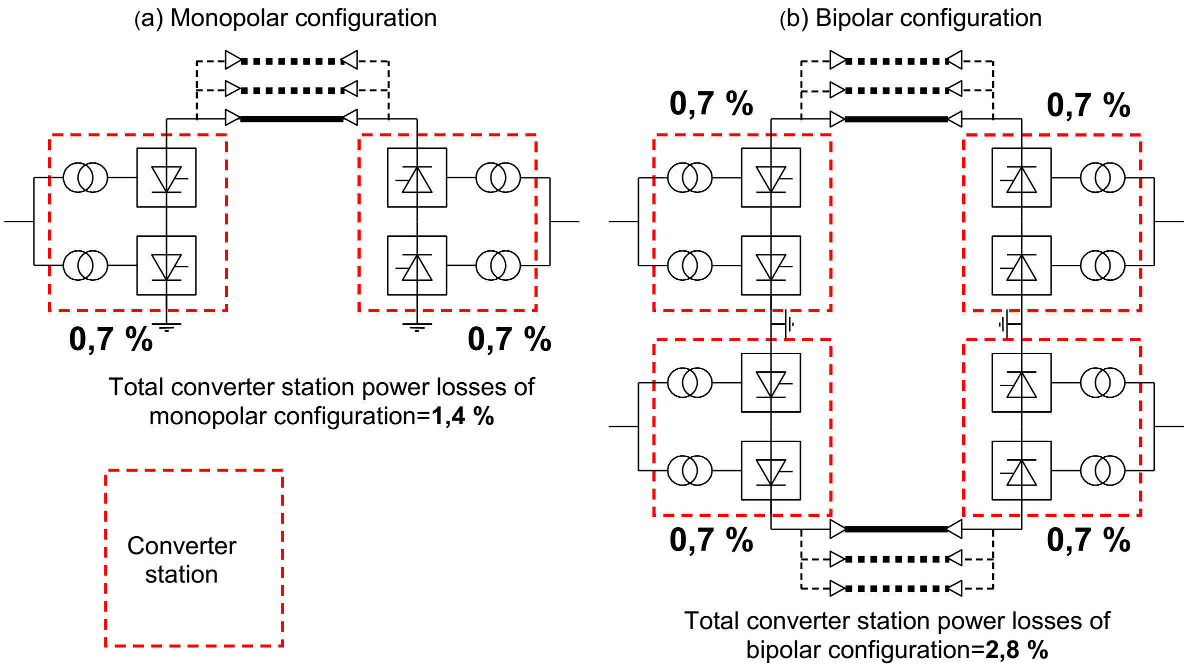
Components		**Operation**	
		Standby	**Rated power**
Filters	**AC**	4%	4%
	DC	0%	<0.1%
Converter transformers		53%	47%
Thyristor valves		10%	36%
Smoothing reactor		0%	4%
Auxiliary systems	**Valve cooling system**	4%	3%
	Transformer cooling system	4%	1%
	Cooling system	15%	4%
	Other systems	10%	1%
Total power losses @20 °C		100%	100%
Power loss Percentage (with reference to rated power)		***0,11%***	***0,70%***

Table D.5 Typical station losses due to each component in HVDC-LCC (after Annex B IEC 61803 [104])

Item	**Typical losses at nominal operating conditions** **%**
Thyristor valves	20-40*
Converter transformers	40-55
AC filters	4-10
Shunt capacitors (if used)	0,5-3
Shunt reactors (if used)	2-5
Smoothing reactor	4-13
DC filters	0,1-1
Auxiliaries	3-10
Total	100

* The total station no-load operation losses range from 10 % to 20 % of the total station operating losses at rated power under nominal operating conditions

Figure. D1 HVDC-LCC: power losses of each converter station as a percentage of rated power for monopolar and bipolar configurations



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