S1. Cost assumptions

Table S1: Overnight investment cost assumptions per technology and year. All costs are given in real 2015 money.

Technology	Unit	2020	2025	2030	2035	2040	2045	2050	source
Onshore Wind	€/kW	1118	1077	1035	1006	977	970	963	[1]
Offshore Wind	€/kW	1748	1660	1573	1510	1447	1431	1415	[1]
Solar PV (utility-scale)	€/kW	529	452	376	352	329	315	301	[1]
Solar PV (rooftop)	€/kW	1127	955	784	723	661	600	539	[2]
OCGT	€/kW	453	444	435	429	423	417	411	[1]
CCGT	€/kW	880	855	830	822	815	807	800	[1]
Coal power plant	€/kW$_{el}$	3845	3845	3845	3845	3845	3845	3845	[3]
Lignite	€/kW$_{el}$	3845	3845	3845	3845	3845	3845	3845	[3]
Nuclear	€/kW$_{el}$	7940	7940	7940	7940	7940	7940	7940	[3]
Reservoir hydro	€/kW$_{el}$	2208	2208	2208	2208	2208	2208	2208	[4]
Run of river	€/kW$_{el}$	3312	3312	3312	3312	3312	3312	3312	[4]
PHS	€/kW$_{el}$	2208	2208	2208	2208	2208	2208	2208	[4]
Gas CHP	€/kW	590	575	560	550	540	530	520	[1]
Biomass CHP	€/kW$_{el}$	3381	3295	3210	3135	3061	2986	2912	[1]
Coal CHP	€/kW	1900	1880	1860	1841	1822	1803	1783	[1]
Biomass central heat plant	€/kW$_{th}$	875	854	832	812	792	773	753	[1]
Biomass power plant	€/kW$_{el}$	3381	3295	3210	3135	3061	2986	2912	[1]
HVDC overhead	€/MWkm	400	400	400	400	400	400	400	[5]
HVDC inverter pair	€/MW	150000	150000	150000	150000	150000	150000	150000	[5]
Battery storage	€/kWh	232	187	142	142	142	142	142	[1]
Battery inverter	€/kW	270	215	160	160	160	160	160	[1]
Electrolysis	€/kW$_{el}$	600	575	550	537	525	512	500	[1]
Fuel cell	€/kW$_{el}$	1300	1200	1100	1025	950	875	800	[1]
H_2 storage underground	€/kWh	3.0	2.5	2.0	1.8	1.5	1.4	1.2	[1]
H_2 storage tank	€/kWh	57	50	44	35	27	24	21	[1]
DAC (direct-air capture)	€/(tCO_2/a)	250	250	250	250	250	250	250	[6]
Methanation	€/kW$_{H_2}$	1000	1000	1000	1000	1000	1000	1000	[7]
Central gas boiler	€/kW$_{th}$	60	55	50	50	50	50	50	[1]
Decentral gas boiler	€/kW$_{th}$	195	190	185	181	176	172	167	[1]
Central resistive heater	€/kW$_{th}$	70	65	60	60	60	60	60	[1]
Decentral resistive heater	€/kWh$_{th}$	100	100	100	100	100	100	100	[7]
Central water tank storage	€/kWh	0.6	0.6	0.5	0.5	0.5	0.5	0.5	[1]
Decentral water tank storage	€/kWh	18	18	18	18	18	18	18	[1, 8]
Decentral air-sourced heat pump	€/kW$_{th}$	940	895	850	827	805	782	760	[1]
Central ground-sourced heat pump	€/kW$_{th}$	564	535	507	494	482	469	456	[1]
Decentral ground-sourced heat pump	€/kW$_{th}$	1500	1450	1400	1350	1300	1250	1200	[1]

Supplemental References

[1] Technology Data for Generation of Electricity and District Heating, update November 2019, Tech. rep., Danish Energy Agency and Energinet.dk (2019).
URL https://ens.dk/en/our-services/projections-and-models/technology-data/technology-data-generation-electricity-and

[2] E. Vartiainen, G. Masson, C. Breyer, The true competitiveness of solar PV: a European case study, Tech. rep., European Technology and Innovation Platform for Photovoltaics (ETIP) (2017).
URL http://www.etip-pv.eu/fileadmin/Documents/ETIP_PV_Publications_2017-2018/LCOE_Report_March_2017.pdf

[3] Lazard's Levelized Cost of Energy Analysis, version 13.0.
URL https://www.lazard.com/media/451086/lazards-levelized-cost-of-energy-version-130-vf.pdf

[4] A. Schröeder, F. Kunz, F. Meiss, R. Mendelevitch, C. von Hirschhausen, Current and prospective costs of electricity generation until 2050, Data Documentation, DIW 68. Berlin: Deutsches Institut.
URL https://www.econstor.eu/handle/10419/80348

[5] S. Hagspiel, C. Jägemann, D. Lindenberger, T. Brown, S. Cherevatskiy, E. Tröster, Cost-optimal power system extension under flow-based market coupling, Energy 66 (2014) 654–666. doi:10.1016/j.energy.2014.01.025.
URL http://www.sciencedirect.com/science/article/pii/S0360544214000322

[6] M. Fasihi, D. Bogdanov, C. Breyer, Long-Term Hydrocarbon Trade Options for the Maghreb Region and Europe—Renewable Energy Based Synthetic Fuels for a Net Zero Emissions World, Sustainability 9 (2) (2017) 306. doi:10.3390/su9020306.
URL https://www.mdpi.com/2071-1050/9/2/306

Table S2: Efficiency, lifetime and FOM cost per technology (values shown corresponds to 2020).

Technology	FOM[a] [%/a]	Lifetime [a]	Efficiency	Source
Onshore Wind	1.2	27		[1]
Offshore Wind	2.3	27		[1]
Solar PV (utility-scale)	1.6	35		[1]
Solar PV (rooftop)	1.2	30		[2]
OCGT	1.8	25	0.4	[1]
CCGT	3.3	25	0.56	[1]
Coal power plant	1.6	40	0.33	[3]
Lignite	1.6	40	0.33	[3]
Nuclear	1.4	40	0.33	[3]
Reservoir hydro	1.0	80	0.9	[4]
Run of river	2.0	80	0.9	[4]
PHS	1.0	80	0.75	[4]
Gas CHP	3.3	25		[1]
Biomass CHP	3.6	25		[1]
Coal CHP	1.6	25	0.48	[1]
Biomass central heat plant	5.8	25	1.03	[1]
Biomass power plant	3.6	25	0.3	[1]
HVDC overhead	2.0	40		[5]
HVDC inverter pair	2.0	40		[5]
Battery storage		20		[1]
Battery inverter	0.2	20	0.95	[1]
Electrolysis	5.0	25	0.64	[1]
Fuel cell	5.0	10	0.5	[1]
H_2 storage underground	0.0	100	0.99	[1]
H_2 storage tank	1.0	25		[1]
DAC (direct-air capture)	4.0	30		[6]
Methanation	3.0	25	0.8	[7]
Central gas boiler	3.2	25	1.03	[1]
Decentral gas boiler	10.5	20	0.97	[1]
Central resistive heater	1.5	20	0.99	[1]
Decentral resistive heater	2.0	20	0.9	[7]
Central water tank storage	0.5	20		[1]
Decentral water tank storage	1.0	20		[1, 8]
Water tank charger/discharger			0.84	
Decentral air-sourced heat pump	3.0	18		[1]
Central ground-sourced heat pump	0.4	25		[1]
Decentral ground-sourced heat pump	1.8	20		[1]

[a] Fixed Operation and Maintenance (FOM) costs are given as a percentage of the overnight cost per year.
[b] Hydroelectric facilities are not expanded in this model and are considered to be fully amortized.
[c] Efficiency for Combined Heat and Power (CHP) plants depends on the electricity/heat output and it is modelled as described in the text.
[d] Coefficient of performance (COP) of heat pumps is modelled as a function of temperature, as described in the text.
[e] Investments in methanation and DAC are not allowed independently, only together as 'Methanation+DAC', see text.

Table S3: Costs and emissions coefficient of fuels.

Fuel	Cost [€/MWh$_{th}$]	Source	Emissions [tCO_2/MWh$_{th}$]	Source
coal	8.2	[9]	0.34	[10]
lignite	2.9	[4]	0.41	[10]
gas	20.1	[9]	0.2	[10]
oil	50.0	[11]	0.27	[10]
nuclear	2.6	[3]	0	
solid biomass	25.2	[12, 13]	0	

[a] Raw biomass fuel cost is assumed as the middle value of the range provided in the references for different European countries and types of sustainable biomass.

[7] K. Schaber, Integration of Variable Renewable Energies in the European power system: a model-based analysis of transmission grid extensions and energy sector coupling, Ph.D. thesis, TU München (2013).
URL https://d-nb.info/1058680781/34

[8] N. Gerhardt, A. Scholz, F. Sandau, H. H., Interaktion EE-Strom, Wärme und Verkehr. Tech. rep. Fraunhofer IWES.
URL http://www.energiesystemtechnik.iwes.fraunhofer.de/de/projekte/suche/2015/interaktion_strom_waerme_verkehr.html

[9] BP Statistical Review of World Energy.
URL https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2019-full-report.pdf

[10] Development of the specific carbon dioxide emissions of the German electricity mix in the years 1990 - 2018, German Environment Agency.
URL https://www.umweltbundesamt.de/sites/default/files/medien/1410/publikationen/2019-04-10_cc_10-2019_strommix_2019.pdf

[11] Word Energy Outlook 2017, International Energy Agency, Tech. rep.

[12] W. Zappa, M. Junginger, M. van den Broek, Is a 100% renewable European power system feasible by 2050?, Applied Energy 233-234 (2019) 1027–1050. doi:10.1016/j.apenergy.2018.08.109.
URL http://www.sciencedirect.com/science/article/pii/S0306261918312790

[13] P. Ruiz, A. Sgobbi, W. Nijs, C. Thiel, F. Dalla, T. Kobert, B. Elbersen, G. H. Alterra, The JRC-EU-TIMES model. bioenergy potentials for EU and neighbouring countries.
URL https://setis.ec.europa.eu/sites/default/files/reports/biomass_potentials_in_europe.pdf