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ESG Economist

Group Economics | 30 April 2024

What are the abatement costs of the key decarbonization technologies?

- In order to decarbonize the world and to become net-zero by 2050 decarbonization technologies play a crucial role
- The costs of these technologies were on a declining trend but such trend has reversed since 2019/2020
- These technologies lower emissions to the extent that own life cycle emissions need to be taken into account as well
- The footprint of the energy mix of a country determines the appropriate technology options to decarbonize
- Lower footprint means fewer decarbonization options and higher marginal abatement costs
- The current ETS carbon price and the marginal abatement costs for the different technologies vary substantially. The ETS price needs to increase strongly and/or technologies need to become cheaper to meet transition goals in a timely matter.

Introduction

The goal is to decarbonize the world and to become net-zero by 2050. Decarbonization technologies play a crucial role in this quest. To achieve this the price of emitting greenhouse gas emissions should be high enough to trigger a change in behavior, and a make low carbon investments viable. In addition, the cost of the important technologies to decarbonize should be attractive enough to stimulate companies to adopt these technologies. Ideally the costs to decarbonize need to be lower than the costs to pay for the greenhouse gas pollution. Here the marginal abatement costs come into play. The abatement cost of an intervention or technology is simply the costs incurred to reduce greenhouse gas emissions by one tonne. In concrete terms, it relates to the total additional costs, which refers to the investment costs plus the difference in operating costs, divided by the avoided emissions. In this report we focus on the marginal abatement costs of the technologies for electricity generation and removal technologies. In these marginal abatement costs, taxes and subsidies are not included. We start with the importance of the energy mix of a country and how this influences the overall abatement costs. Then we look at the costs of the decarbonization technologies. We conclude this piece with the marginal abatement costs per technology.

The importance of the energy mix

In this section, we show the impact of the different technologies in the energy mix on the avoided emissions. The avoided emissions are in grams CO2eq per kWh. CO2eq is a metric measure used to compare the emissions from various greenhouse gases on the basis of their global-warming potential (GWP), by converting amounts of other gases to the equivalent amount of carbon dioxide with the same global warming potential. Global Warming Potential is a term used to describe the relative potency, molecule for molecule, of a greenhouse gas, taking account of how long it remains active in the atmosphere. Kilowatt-hour or kWh is a unit of measure for energy usage. One kilowatt is equal to 1,000 watts.

We start with the global picture in 2022. The fossil fuel mix of global electricity generation is 36% coal, 23% gas, 15% hydro, 9% nuclear 7% wind and 5% solar and some others. The footprint of this energy mix is around 507 gr CO2eq per kWh.

Europe has a different energy mix than the global average. For Europe in 2022, the energy mix is 17% coal, 26% gas, 15% hydro, 19% nuclear, 11% wind and 5% solar. Because of the lower share of coal, but the higher share of nuclear and wind, the footprint is lower namely around 324 gr CO2eq per kWh. Every country has its own energy mix and therefore is own footprint. Why is this important in calculating marginal abatement costs? If a country has a higher footprint, more technologies are attractive for abatement while if the footprint is lower, fewer technologies are attractive to abate because the total avoided emissions are lower, and this translates into higher marginal abatement costs per technology (more on this later in this report). In the table below we set out an overview of the life cycle assessment emissions of the major electricity generation technologies and the footprint of the energy mix per country.

Life cycle emissions per technology

In grams per CO2eq per kWh

	Europe	Germany	France	Spain	NL	US	Global
Energy mix footprint 2022	**324**	**409**	**61**	**172**	**302**	**386**	**507**
Electricty generation							
Coal	1023	1023	1023	1023	1023	820	820
Coal with Carbon Capture and Storage (CCS, -64% emissions)	369	369	369	369	369	295	295
Gas							
Combined Cycle Gas Turbine (CCGT)	340	340	340	340	340	340	340
CCGT with CCS (-70%)	102	102	102	102	102	102	102
CCGT hydrogen	289	289	289	289	289	289	289
Open-Cycle Gas Turbine (OCGT)	520	520	520	520	520	520	520
OCGT with CCS (-70%)	156	156	156	156	156	156	156
OCGT hydrogen	289	289	289	289	289	289	289
Wind							
Onshore	12	12	12	12	12	11	12
Offshore	14	14	14	14	14	14	14
Solar							
Utility scale	41	41	41	41	41	36	41
Hydro	11	11	11	11	11	11	11
Nuclear	5	5	5	5	5	5	5
Geothermal	45	45	45	45	45	45	45
Bio energy	230	230	230	230	230	230	230

Source: ABN AMRO Group Economics, Irena, EMBER, Bloomberg NEF, NREL, Unece, IEA, GREEN-NCAP, ICCT, Argonne National laboratory, MIT CEEPR WP2022-017, World Resource Institute, scientific reports

On the one hand, France has the lowest footprint because 65% of its electricity is generated by nuclear, which has a low emissions per kWh generated (see more here). But the results of the life cycle emissions of nuclear vary considerably depending on the type of reactor. According to a study (see more here) the average carbon emissions of the different type of reactors vary between 4 and 43 grams CO2 per kWh.

On the other hand, the electricity mix of Germany has one of the highest footprint in this overview. This is because Germany uses quite a lot of coal. For example, it has still 27% of coal compared to only 2% in France. But the high percentages of solar and wind compensate partly for the considerable use of coal in Germany.

The Netherlands also has a high share of solar and wind but also a high share of natural gas. As this emits lowers CO2eq per kWh, the overall footprint is lower than Germany, but higher than France.

For the marginal abatement costs, the avoided emissions are important. This is the difference between the footprint of the energy mix of a country and the life cycle emissions of a technology. For example, Germany has a footprint of 409 grams CO2eq per kWh electricity generated. Solar has life cycle emissions of forty-one grams CO2eq per kWh. So, the avoided emissions if you were to use only solar would be 409 – 41 = 368 grams CO2eq per kWh. This would decrease the footprint of Germany significantly. For France, solar would also reduce emissions, but to a much lesser extent. The avoided emissions would be 61 – 41 = 20 grams CO2eq per kWh. This means that for any given cost of the same technology, the abatement cost would be much higher.

Costs per technology

Next to the energy mix, the total additional costs of the electricity generated also have an impact on the marginal abatement costs. For this, we have taken the levelized costs of electricity (LCOE) of the renewable technologies excluding taxes and subsidies. LCOE is the present value of the total costs over the lifetime divided by the present value of all electricity generated over the lifetime. The outcome is the costs in US dollars per kWh of electricity. Between 2010 and 2022 the levelized costs of electricity for the major renewable technologies declined substantially (see table below). Indeed, the levelized costs of electricity for solar declined by 89%, concentrated solar power and onshore wind by close to 70% and offshore wind by close to 60%. Lower levelized costs of electricity also drive down the marginal abatement costs for the different technologies. Only the costs for hydropower and geothermal increased during this period.

Levelized cost of electricity 2010-2022

In USD per kWh

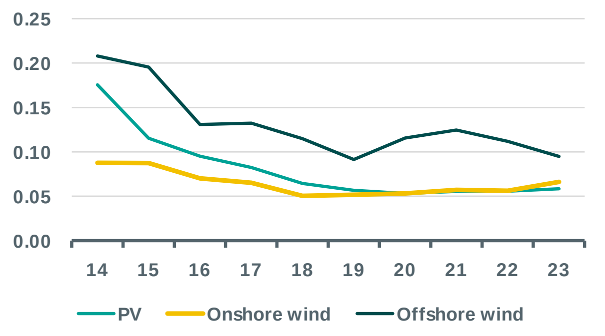
	Levelised cost of electricity (2022 USD/kWh) 2010	2022	Percent change
Bioenergy	0.082	0.061	-25%
Geothermal	0.053	0.056	6%
Hydropower	0.042	0.061	47%
Solar PV	0.445	0.049	-89%
Concentrated Solar Power	0.380	0.118	-69%
Onshore wind	0.107	0.033	-69%
Offshore wind	0.197	0.081	-59%

Source: Irena

The same trend is seen for solar and wind for Germany and the Netherlands, but in recent years the decline in levelized costs of electricity for these technologies has slowed down or even partly reversed (see graphs below). For Germany, PV and onshore wind were the cheapest in 2020 and then the levelized cost of electricity has increased modestly. For the Netherlands, offshore wind was the cheapest in 2019 and onshore wind in 2020. Since then, these technologies have become more expensive. Indeed, between 2019 and 2023 the costs of offshore wind for the Netherlands have increased by 87% and 49% in 2023 according to Bloomberg NEF. During 2020 and 2023 onshore wind costs increased by 12% for the Netherlands and half of that was in 2023.

LCOE Germany for selected renewable technologies

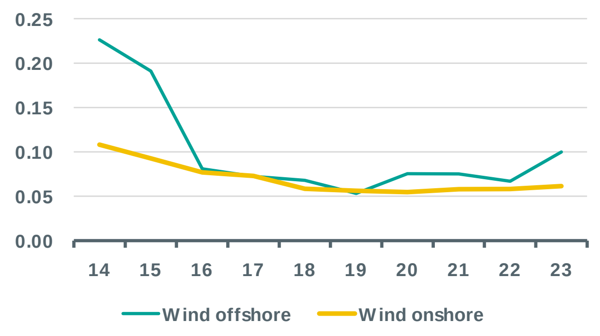
In USD per kWh



Source: Bloomberg NEF

LCOE Netherlands for wind

In USD per kWh



Source: Bloomberg NEF

Marginal abatement costs

We have focused on the footprint of the energy mix (in grams CO2eq per kWh), the avoided emissions (in grams CO2eq per kWh) and the levelized costs of electricity of the different technologies (in USD per kWh). Now it is time to bring these elements together as they are the input variables for calculating the marginal abatement costs (in USD per tonne CO2eq, 1 tonne = 1 million grams). As there is a lack of data of the levelized costs of electricity of the different technologies for the different countries, we have used the data of Germany for the other European countries.

The table below shows the marginal abatements costs for the different technologies. An "x" means that this technology will not result in lower emissions compared to the current energy mix. Some of the technologies show extremely high prices such as coal with CCS, or gas with CCS. This reflects that coal or gas with CCS will only have a limited amount of avoided emissions compared to the energy mix, while total costs are elevated. Therefore, the marginal abatement costs of these technologies are extremely high for Germany. For the US, the lower levelized costs of electricity compensated partly for this. The most attractive options for the US are onshore wind, solar and geothermal (see table below).

France has fewer options to abate. This is because quite a number of these technologies have a higher footprint than the energy mix. Even if these technologies have a lower emissions per kWh, the avoided emissions will be relatively low pushing up the marginal abatement costs. Therefore, the marginal abatements costs are remarkably high.

Germany has one of the highest footprint in this overview. Therefore, it has more options to lower emissions and the abatement costs are also lower than compared to for example of France. For Germany solar, geothermal and onshore wind are the most attractive options.

Marginal abatement costs

USD per tonne CO2eq

	Europe	Germany	France	Spain	NL	US	Global
Electricty generation							
Coal	x	x	x	x	x	x	x
Coal with Carbon Capture and Storage (CCS, -64% emissions)	x	9583	x	x	x	1905	554
Gas							
Combined Cycle Gas Turbine (CCGT)	x	3463	x	x	x	1522	698
CCGT with CCS (-70%)	690	559	x	2167	940	275	293
CCGT hydrogen	6049	2564	x	x	x	2432	1059
Open-Cycle Gas Turbine (OCGT)	x	x	x	x	x	x	x
OCGT with CCS (-70%)	3256	2489	x	31111	5000	965	1236
OCGT hydrogen	15459	6553	x	x	x	6215	2705
Wind							
Onshore	190	179	1284	328	239	139	86
Offshore	239	259	4976	594	394	428	480
Solar							
Utility scale	226	171	3533	308	394	180	104
Hydro	262	224	1832	508	323	221	122
Nuclear	1264	1085	8016	2416	1552	979	789
Geothermal	226	171	3533	308	394	180	104
Bio energy	939	609	x	x	2421	391	216
Carbon removal technologies							
Carbon Capture & Storage							70-250
Direct Air Capture							250-1,600
Reforestation							10-50

Source: ABN AMRO Group Economics, Irena, EMBER, Bloomberg NEF, NREL, Unece, IEA, GREEN-NCAP, ICCT, Argonne National laboratory, MIT CEEPR WP2022-017, World Resource Institute, scientific reports

In the table above there are also the marginal abatement costs for carbon removal technologies. These costs are in USD per tonne CO2 while the other marginal abatement costs in the table are in USD per CO2eq. Reforestation is clearly the most attractive option. The abatement cost for Direct Air Capture has a wide range. This technology is energy intensive because of the low concentration of CO2 in the atmosphere and its efficiency depends on if renewables are used or not for the electricity generation.

As mentioned above the marginal abatement costs are in USD per tonne CO2eq while the ETS price is for one tonne of CO2 (without the impact of other greenhouse gasses). Even if we were to take it as a guide, the ETS price and the marginal abatement costs deviate substantially. This indicates that the technologies need to become cheaper and or the ETS price needs to rise considerably for the transition to become viable. What is more, the marginal abatement costs tend to rise if the footprint of the energy mix declines. So, this could put a more upside pressure to the needed ETS price. An option to lower the marginal abatement costs is to introduce or increase subsidies for certain technologies.

Conclusion

The goal is to decarbonize the world and to become net-zero by 2050. To achieve this, decarbonization technologies play a crucial role. Between 2010 and 2022 most of the costs of renewable technologies declined substantially, but recently some have become more expensive again. Applying these technologies will result in lower emissions for the energy mix of the electricity generation. But as they also have life cycle emissions, only the difference between these emissions and the footprint of a country's energy mix can be taken as avoided emissions. The footprint of the energy mix directly affects the avoided emissions for each technology in each country. Lower footprint of the energy mix and thereby lower avoided emissions tend to increase the marginal abatement costs. Therefore, if countries are successful in lowering the footprint of the energy mix, it will be more difficult to find attractive options to decarbonize further. Overall, the marginal abatement costs deviate substantially from the ETS price. So, the ETS price has to increase sharply and/or these technologies need to become cheaper in order to achieve the transition in a timely manner.

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