

Levelised Cost of Electricity

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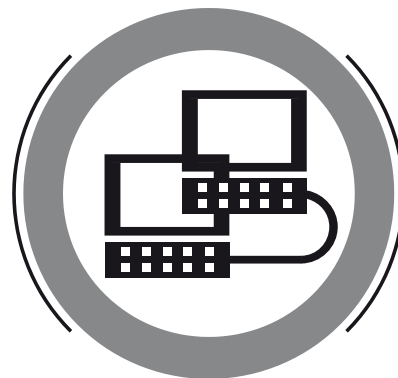


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1. Introduction

The Levelised Cost of Electricity (LCOE) method allows comparing power plants with different power generation and costing structures. The fundamental idea is to calculate yearly average costs of building and operating the plant, and to compare this with the average annual energy generated. This provides the LCOE in Euro cents per kWh.

The continuous changing situation and constraints of the European Electricity Market led the VGB Executive Board to the decision to place the order to the VGB office for a new edition of VGB's recurring published LCOE. The ambition is to provide our members, policymakers and other stakeholders with a comprehensive and robust set of 'order of magnitude' data. The main considerations of the new edition:

- Focus on Europe
- Coverage of major electricity generation technologies
- Displaying a bandwidth of LCOE
- Calculation basis from latest studies, own resources and VGB-Member data
- Application of a public and proven available LCOE programme
- Transparency of the input data and the calculation
- Attainment of a high degree of transparency by alignment with the members of the VGB Technical Advisory Board and the VGB Strategic Forums Wind & Hydro.

The calculation was performed under the premises to provide a minimum (best) and maximum (worst) case situation of Levelised Cost of Electricity. The methodology is focused but not limited on baseload generation in stable market conditions. A determination of the economic viability of any specific plant is not possible due to the limitations of the LCOE approach; we refer to chapter 6 that describes the limitations in detail.

2. Methodology

To compare the cost of electricity production of different technologies, the total specific cost of each technology is calculated over the entire lifetime of the power plant and an average LCOE is calculated. The cost for electricity produced by different power generation technologies is calculated under different assumptions. For simplification the methodology applied is based on a single input parameter overall years considered - for example only one price for CO₂ certificates is assumed for the entire lifetime of a power plant.

In detail the LCOE is calculated on the basis of a dynamic procedure, which calculates the LCOE over a period of operation. The starting point is an annual cost analysis, which considers the costs of each operating year separately.

The cost components of capital costs, operating costs and fuel costs during plant operation are added up for each year. The capital-related costs fall over time according to the weighted average cost of capital (WACC), and the fuel prices generally tend to increase, depending on the fuel price scenario selected. The overall costs are thus different each year.

The annual overall costs would result in a different LCOE for each operating year. This approach is not helpful for comparing various power plant technologies, however, and the cost components are therefore added up over the entire technical service life, discounted against current value (WACC), and compared to the net power generation. This allows the financial calculation of average annual costs during operation.

The following equation shows that the amount of spending is equal to the total return:

$$\sum_{t=0}^T \frac{\bar{p} \cdot E_t}{1 + r_t} - \sum_{t=0}^T \frac{I_t + M_t + F_t}{(1 + r)^t} = 0$$

Thereof the average electricity production costs \bar{p} can be derived as follows:

$$\bar{p} = \frac{\sum_{t=0}^T \frac{[I_t + M_t + F_t]}{(1 + r)^t}}{\sum_{t=0}^T \frac{[E_t]}{(1 + r)^t}}$$

I_t = Capital expenditure in the year t

M_t = Operating and maintenance costs in the year t

F_t = Fuel price expenditures in the year t

E_t = Net electricity production in the year t

r= Discount rate

\bar{p} = Average electricity production costs

The detailed calculation methodology is explained in detail in the public available LCOE programme in the tab "LCOE formula". The LCOE programme is available on the web page of the Agora Energiewende, a part of Smart Energy for Europe Platform (SEFEP) gGmbH that is a joint initiative of the Mercator Foundation and the European Climate Foundation <http://www.agora-energiewende.de/en/service/daten-tools/>

Some annotations are necessary; in any general model only a few parameters can be included, and a lot of factors that have not been considered influence costs. This report on LCOE regards the levelised cost of producing baseload electricity. This is a straightforward strategy with implications that are frequently less obvious.

As described above the methodology of LCOE assumes a baseload market, but this approach only partly exists for hard coal, lignite and gas CCGT power plants in Europe. In consequence this is a discrimination of these electricity generation types. To cover both situations the baseload and the current market are calculated for LCOE in an Ideal Case and a Real Case.

Secondly, operational costs ignore the impact of a power generation system on the electricity system as a whole. This is an issue affecting all technologies, for instance in terms of location or grid connection. The issue of system externalities, however, is vital for variable (non dispatchable) renewable energies, such as wind and solar. In case of profound electricity generation of variable renewable energy electricity cannot currently be stored in such an amount that at every second demand and supply is balanced.

The ability to balance the system is a burden for the non-dispatchable availability of electricity from wind turbines or solar panels. Meteorology can help but is not decisive. Even shortfalls announced in advance must be compensated by other sources of generation that can be mobilised on short notice, namely hydro or thermal power plants. In principle part of the cost of such system reserves should, be added to the LCOE of non-dispatchable renewables when compared to other baseload generation sources. But the report focuses only on technical system costs.

Input data used for the calculation of electricity production costs are current studies/publications (chapter 8), data of VGB Member companies and own sources.

3. Electricity generation types

3.1 Coal and lignite supercritical power plants

There is no standard definition for supercritical versus ultra-supercritical power plants, though in general any plant that operates above 600°C is considered to be ultra-supercritical. Typical supercritical and ultra-supercritical plants use steam at pressures from 240 bar to 300 bar and temperatures up to 620°C.

3.2 CCGT and OGCT

CCGT is the dominant gas-based technology for intermediate and base-load power generation. These plants have the same basic components as the OCGT plants, but the heat associated with the gas-turbine exhaust is used in a heat recovery steam generator (HRSG) to produce steam that drives a steam turbine and generates additional electric power.

3.3 Nuclear power

The nuclear power plant types currently under construction and planning within Europe were taken into consideration. These are pressurised water reactors (PWR) and nuclear power plants of the third generation.

3.4 Run-of-the-river plant

Run-of-the-river plant is considered to be ideal for streams or rivers with a minimum dry weather flow or those regulated by a much larger dam and reservoir upstream. Pumped storage power plants are not considered in this survey to avoid any misinterpretation.

3.5 Onshore and offshore wind

Wind farms that are inland (onshore) or close to the coast, or off the coast at sea (offshore), were considered.

3.6 Ground-mounted PV systems

Ground-mounted PV systems are usually large, utility-scale photovoltaic power stations. The PV array consists of solar modules held in place by racks or frames that are attached to ground-based mounting supports.

4. Cost components

4.1 Investment cost

The investment costs are capital expenditures in the process of building an electricity generation plant, relative to the installed electrical net output. This includes cost components that are directly and indirectly related to the building and commissioning of the plant, or cost components that are incurred by the plant operator before or during the construction process. Demolition costs are not comprised in the Investment Costs.

4.2 Discount rate

When calculating the LCOE, a minimum rate of 4% and a maximum rate of 7% were used for all technologies to cover differences for peak load, baseload and renewables.

4.3 Plant Lifetime

For each technology, an average lifetime was estimated across the European countries in the following manner. Coal and lignite-fired power plants have a lifetime of 40 years. Natural gas-fired CCGT and OGCTs have a lifetime of 30 years. Nuclear power plants have a lifetime of 60 years. Hydropower has a lifetime of 100 years and wind and photovoltaic plants have a lifetime of 25 years.

4.4 O&M

The costs of plant operation include all the costs of power generation that are not associated with the initial investment (see above) or the use of an energy carrier (fuel costs, including transport costs and any taxes) or CO₂ certificate costs. These include the costs of maintenance, and expenses for auxiliary and operating materials, personnel, administration and insurance. A spread of O&M costs is appropriate to respect different strategies and operation hours.

4.5 Fuel costs

Only one value of fuel costs for each technology is too short-sighted to consider the influences of for e.g. various sources, qualities, price developments. A spread of around $\pm 20\%$ on the price below is implemented.

Hard coal

Based on information provided by power plant operators, the average price in 2014 for power plant hard coal was € 9 per MWh free delivery at the German border.

Lignite

It is quite common to calculate only the variable costs of extraction, which come to around € 1.50 per MWh. The price for domestic lignite has to include also the investments in the development of the mine. A price of € 5 per MWh is estimated to have the same condition as hard coal that comprises development costs.

Natural gas

The analysis of the import control and Intrastat data for Germany relating to Russian, Dutch, Norwegian, Danish and British gas for 2014 showed a border price of € 23.5 per MWh. The natural gas border price was applied for CCGT as well for OGCT.

Nuclear power

For uranium prices, an indicative value that does not directly enter the calculation of the front-end of the nuclear fuel cycle is € 75 per kg of U₃O₈, which has been the average price during the last 50 years. A fuel price of € 7 per MWh was calculated, including mining, enrichment, conditioning (front-end of nuclear fuel cycle), as well as spent fuel removal, disposal and storage (back-end of nuclear fuel cycle).

4.6 Carbon price

Currently (05/2015) the auction price on the EEX Leipzig for EU emissions allowances (EUA) is € 7.5 per t CO₂. The Carbon price was volatile in the past and also expected in the future. A bandwidth is implemented to reflect the situation.

4.7 Electrical efficiency

A minimum and maximum electrical efficiency was taken to cover the technology range of fuel conversion into net power output for Coal, Gas and Nuclear power plants. Depending on technology, the minimum efficiency is below the maximum efficiency, and takes into consideration factors such as air temperature, humidity, degradation etc. The maximum efficiency refers to the operation of the plant at its best operating point (new and clean).

4.8 Carbon factor

The CO₂ emission factors of the three most important fossil fuels in the European electricity mix are hard coal at 339 kg CO₂ per MWh_{th}, lignite at 404 kg CO₂ per MWh_{th}, and natural gas at 202 kg CO₂ per MWh_{th}.

4.9 Full-load hours

Full-load hours were split in minimum and maximum values, in order to take into account the changing situation of the current electricity market and in future.

5. LCOE calculation

The LCOE is calculated under the premises to create a best (min) and worst (max) case optimum of Levelised Cost of Electricity. The input values of the Minimum LCOE and Maximum LCOE are given below and in the following spreadsheets. The LCOE results of the different technologies are displayed in the next spreadsheets and charts.

I. The **Minimum LCOE** (green, flow chart above table) has nine input values:

- Min Investment Cost
- Min Discount Rate
- Lifetime
- Min O&M
- Min Fuel Costs
- Min Carbon Price
- Max Electrical Efficiency
- Carbon Factor
- Max Full-Load Hours.

II. The **Maximum LCOE** (red, flow chart below table) has nine input values:

- Max Investment Cost
- Max Discount Rate
- Lifetime
- Max O&M
- Max Fuel Costs
- Max Carbon Price
- Min Electrical Efficiency
- Carbon Factor
- Min Full-Load Hours.

5.1 Full-load hours


The methodology of LCOE assumes a baseload market, but this approach only partly exists for hard coal, lignite and gas CCGT power plants in Europe. In consequence is this a discrimination of these electricity generation types. Thus the approach was modified for hard coal, lignite and gas CCGT power plants and two scenarios introduced. The **Real Case** reflects the current operation hours in the electricity market and the so called **Ideal Case** focuses on the general optimum range.

The first scenario mirrors the **Real Case** and the second scenario the **Ideal Case**.

Levelised Cost of Electricity (LCOE)


"Real Case"

Min LCOE Calculation =>



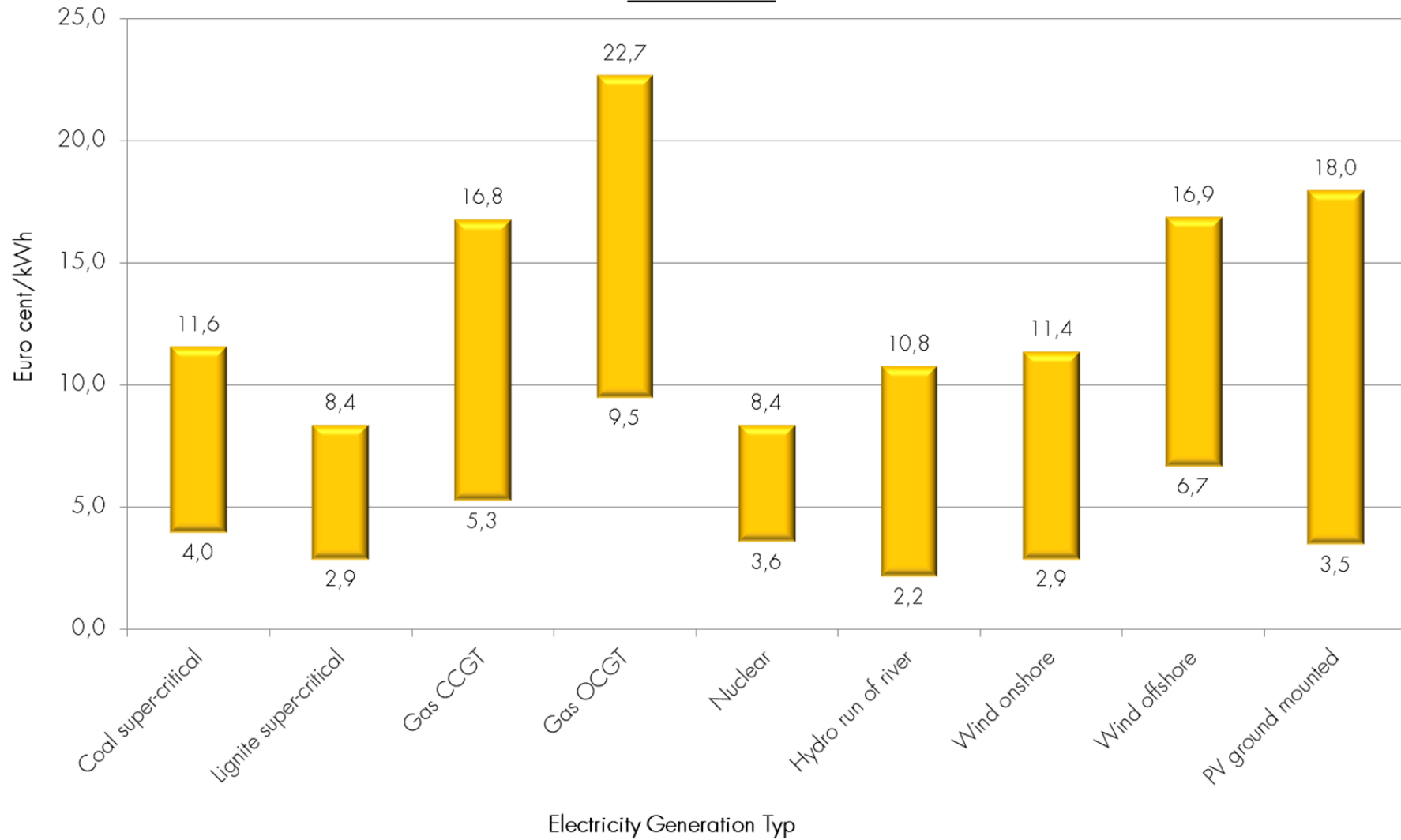
	Investment Cost (€/kW) ^{1, 7, 8, 11}		Discount Rate (%) ¹¹		Lifetime (y) ¹	O&M (€/kW/a) ^{5, 6, 7, 8,}		Fuel Costs (€/MWh) ^{1, 2, 9}		Carbon price (€/tCO ₂) ³		Electrical Efficiency ¹¹		Carbon Factor (tCO ₂ / MWh _{th})	Full Load Hours (h) ^{1, 8, 10, 11}		LCOE (ct/kWh)	
	Min	Max	Min	Max		Min	Max	Min	Max	Min	Max	Min	Max		Min	Max	Min	Max
	Coal supercritical	1.200	1.700	4		7	40	32	39	7	11	5	10		44	46	0,339	2.000
Lignite supercritical	1.350	1.800	4	7	40	35	43	4	6	5	10	41	43	0,404	3.000	7.000	2,9	8,4
Gas CCGT	550	800	4	7	30	19	23	19	28	5	10	59	61	0,202	750	2.500	5,3	16,8
Gas OCGT	400	720	4	7	30	14	17	19	28	5	10	39	44	0,202	500	750	9,5	22,7
Nuclear	3.000	5.000	4	7	60	36	44	6	9	-	-	32	37	-	7.000	8.000	3,6	8,4
Hydro run of river	2.300	4.500	4	7	100	25	50	-	-	-	-	-	-	-	3.400	5.500	2,2	10,8
Wind onshore	1.000	1.800	4	7	25	30	50	-	-	-	-	-	-	-	1.800	3.200	2,9	11,4
Wind offshore	2.800	4.500	4	7	25	100	120	-	-	-	-	-	-	-	3.000	4.200	6,7	16,9
PV ground mounted	900	1.600	4	7	25	13	25	-	-	-	-	-	-	-	900	2.000	3,5	18,0

Max LCOE Calculation =>

- 
- 1) OECD/IEA Study, 2015
 - 2) BAFA
 - 3) EEX, Leipzig
 - 4) Umweltbundesamt
 - 5) IER, Stuttgart, 2008
 - 6) IER, Stuttgart, 2012
 - 7) DIW, Berlin, 2012
 - 8) EC DG Energy, ECOFYS, 2014
 - 9) Bundesnetzagentur
 - 10) ISE, Freiburg, 2013
 - 11) Own resources and VGB-Members

All performance specific input data relate to the electrical net power, the power supply to the grid.

Levelized Cost of Electricity (LCOE) "Real Case"



Levelised Cost of Electricity (LCOE) "Ideal Case" for Coal, Lignite and Gas CCGT Power Plants

Min LCOE Calculation =>

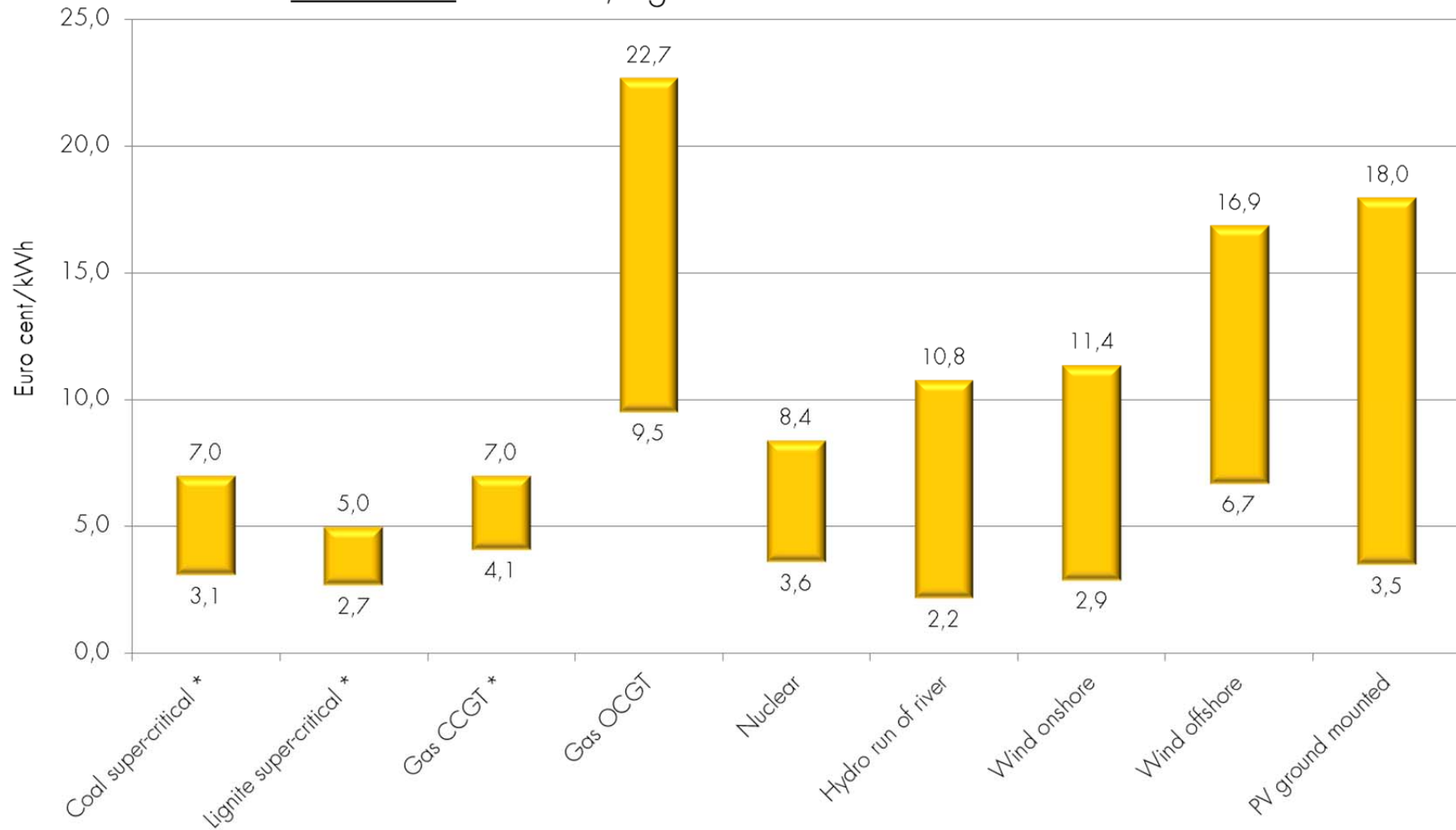
	Investment Cost (€/kW) ^{1, 7, 8, 11}		Discount Rate (%) ¹¹		Lifetime (y) ¹	O&M (€/kW/a) ^{5, 6, 7, 8,}		Fuel Costs (€/MWh) ^{1, 2, 9}		Carbon price (€/tCO ₂) ³		Electrical Efficiency ¹¹		Carbon Factor (tCO ₂ / MWh _{th})	Full Load Hours (h) ^{1, 8, 10, 11, +}		LCOE (ct/kWh)	
	Min	Max	Min	Max		Min	Max	Min	Max	Min	Max	Min	Max		Min	Max	Min	Max
	Coal supercritical ⁺	1.200	1.700	4		7	40	32	39	7	11	5	10		44	46	0,339	4.500
Lignite supercritical ⁺	1.350	1.800	4	7	40	35	43	4	6	5	10	41	43	0,404	7.000	8.000	2,7	5,0
Gas CCGT ⁺	550	800	4	7	30	19	23	19	28	5	10	59	61	0,202	4.500	6.500	4,1	7,0
Gas OCGT	400	720	4	7	30	14	17	19	28	5	10	39	44	0,202	500	750	9,5	22,7
Nuclear	3.000	5.000	4	7	60	36	44	6	9	-	-	32	37	-	7.000	8.000	3,6	8,4
Hydro run of river	2.300	4.500	4	7	100	25	50	-	-	-	-	-	-	-	3.400	5.500	2,2	10,8
Wind onshore	1.000	1.800	4	7	25	30	50	-	-	-	-	-	-	-	1.800	3.200	2,9	11,4
Wind offshore	2.800	4.500	4	7	25	100	120	-	-	-	-	-	-	-	3.000	4.200	6,7	16,9
PV ground mounted	900	1.600	4	7	25	13	25	-	-	-	-	-	-	-	900	2.000	3,5	18,0

Max LCOE Calculation =>

- | | | | |
|-------------------------|-------------------------|-------------------------------|---|
| 1) OECD/IEA Study, 2015 | 4) Umweltbundesamt | 7) DIW, Berlin, 2012 | 10) ISE, Freiburg, 2013 |
| 2) BAFA | 5) IER, Stuttgart, 2008 | 8) EC DG Energy, ECOFYS, 2014 | 11) Own resources and VGB-Members |
| 3) EEX, Leipzig | 6) IER, Stuttgart, 2012 | 9) Bundesnetzagentur | +) LCOE with ideal min/max Full-Load Hours |

All performance specific input data relate to the electrical net power, the power supply to the grid.

Levelized Cost of Electricity (LCOE) "Ideal Case" for Coal, Lignite and Gas CCGT Power Plants



*) LCOE with ideal min/max Full-Load Hours

Electricity Generation Typ

6. Limitations of LCOE in deregulated markets

A rate-regulated electricity market is the foundation for the LCOE methodology. The primary aims are:

- to rank different available technologies for power production by average lifetime cost
- to assess the level of electricity tariffs.

All plant-level costs (investments, fuel, emissions, operation and maintenance, dismantling, etc.) summed up to calculate LCOE and dividing them by the quantity of the generated electricity, after an appropriate discounting. The LCOE represents the average lifetime cost for providing a MWh for given full-load hours. A straightforward comparison of technologies is allowed by this simple metric for different size, different lifetimes and a different profile of expenditures. The foundation of the LCOE methodology is “baseload” power generation. Baseload generation is required because of an incompressible “base” of demand remaining constant throughout the year. The full-load hours of dispatchable technologies for baseload power generation, such as nuclear, coal or combined-cycle gas turbines, are thus considered to be highly corresponding to their technical availability in LCOE calculations.

The LCOE methodology implies several advantages and is in addition the appropriate tool for answering key questions of regulators:

- Simple
- Transparent (in particular with respect to its assumptions, all of which are easily made explicit)
- Comparable across technologies.

The close link of the LCOE methodology to the ubiquitous and well-understood financial notion of net present value has always increased its appeal (i.e. LCOE is the constant price of electricity for which the net present value (NPV) is equal to zero). This has led to applying the LCOE methodology also for cost comparisons in deregulated markets as well but with limitations.

LCOE relates to the costs at the level of the chosen technology up to the connection to the electricity grid. By definition, these costs do not consider any effects at the system level in the sense that specific technologies demand additional investments in transmission and distribution grids or specific additional reconfigurations of the electricity systems such as flexibility or added capacity provision.

The estimation of each category of system costs is a very complex undertaking, and there is not a common methodology applied and accepted internationally. Applying the results is generally not possible to a different context or extrapolating the analysis to different penetration levels. Any undertaking to do so would need additional analysis to guarantee that results are robust.

LCOE results are influenced by:

- the definition of system costs
- the definition of boundaries between categories
- the time horizon (short-term vs. long-term) and assumptions about the ability of the power system to adapt
- assumptions about future parameters, including fuel and CO₂ prices

The fact remains in liberalised electricity markets introduced in many OECD countries since the 1990s that the LCOE methodology is not particularly well-suited to assess the competitiveness of different generation technologies.

Competitive electricity markets establish prices that reflect the marginal costs rather than average costs that underlie LCOE accounting independent from system issues.

Especially, LCOE is of limited practicability once electricity prices are an input rather than an output of investors' profitability calculations. Investors calculate the NPV to assess whether the cash flow of a new project is sufficient to reimburse the investment and capital costs used to finance a project. NPV calculations are based on expected external electricity prices and allow to consider their variation and uncertainty over time. A negative NPV will not deliver sufficient information to investment in a project but even a positive NPV is not appropriate for the investment question in a project.

Last but not least, LCOE calculations are a special form of NPV calculation, whose output is an internally determined electricity price that will equal NPV to zero. The key limitation is that the electricity price is assumed to be constant from the day of commissioning of a power plant until the last day of operation. Out of this reason, the LCOE methodology cannot directly compete with markets where the market establishes prices and where risks are important. Sensitivity analysis of LCOEs to discount rates reflect to some extent the risk-adjusted cost of capital, but this is not sufficient, as it ignores the different abilities of different technologies to address short-term and long-term price risks.

The perspective of individual companies can differ from this cost comparison.

7. References

1. Projected Costs of Generating Electricity, 2015 Edition, IEA, NEA, OECD
2. BAFA (Bundesamt für Wirtschaft und Ausfuhrkontrolle / Federal Office for Economic Affairs and Export Control); <http://www.bafa.de/bafa/en/>
3. EEX (European Energy Exchange AG); www.eex.com
4. Umweltbundesamt / Federal Environment Office; <http://www.umweltbundesamt.de/en>
5. Stromerzeugungskosten im Vergleich / Comparison of Electricity Production Costs, S. Wissel, S. Rath-Nagel, M. Blesl, U. Fahl, A. Voß; Report No. 4, February 2008; IER Stuttgart
6. Stromerzeugung 2030 – mit welchen Kosten ist zu rechnen?; Markus Blesl, Steffen Wissel und Ulrich Fahl; Energiewirtschaftliche Tagesfragen 62. Jg. (2012) Heft 10
7. Current and Prospective Costs for Electricity Generation - Background Paper for the Project "Modeling the Energy Transformation" and Other Modeling Exercises; Andreas Schröder, DIW Berlin, (2012)
8. Subsidies and costs of EU energy; Sacha Alberici, Sil Boeve, Pieter van Breevoort, Yvonne Deng, Sonja Förster, Ann Gardiner, Valentijn van Gastel, Katharina Grave, Heleen Groenenberg, David de Jager, Erik Klaassen, Willemijn Pouwels, Matthew Smith, Erika de Visser, Thomas Winkel, Karlien Wouters; Ecofys 2014 by order of: European Commission
9. Bundesnetzagentur / Federal Network Agency; <http://www.bundesnetzagentur.de>
10. Stromgestehungskosten Erneuerbare Energien, Fraunhofer-Institut für Solare Energiesysteme (ISE); Christoph Kost, Johannes N. Mayer, Jessica Thomsen, Niklas Hartmann, Charlotte Senkpiel, Simon Philipps, Sebastian Nold, Simon Lude, Thomas Schlegl; 2013
11. Calculator of Levelized Cost of Electricity for Power Generation Technologies of AGORA; Daniel Fürstenberg; February 2014; <http://www.agora-energiewende.de/de/service/daten-tools/>

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