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Exceeding LCOE: Calculating Energy Costs in Energy Policy Design

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Key Conclusions

- **The Levelized Cost of Electricity (LCOE) has been widely used for over 50 years, primarily due to its calculation simplicity. It represents only the cost of generating electricity from a given source. However, it does not account for all other elements of a unit's operation within the power system—such as grid integration costs and the balancing of the electricity system through dispatchable energy sources**. A key characteristic of LCOE is its focus on financial viability while minimizing exposure to risk for **investors and the financial sector**.
- The widespread use of LCOE significantly underestimates the actual costs of non-dispatchable energy sources (such as photovoltaics and wind farms) by failing to account for the infrastructure costs required to maintain a stable electricity supply, even during multi-day dark doldrums. Notably, these costs increase as the share of non-dispatchable sources in the energy mix grows.
- In 2023, the share of non-dispatchable sources in Poland's electricity mix exceeded 21%. This indicates that Poland is approaching a threshold beyond which the costs of integrating non-dispatchable sources into the power system will rise significantly. Therefore, the use of additional indicators to assess the competitiveness of different technologies becomes even more critical.
- Northern and Central European countries frequently experience the phenomenon known as the dark doldrums—a combination of low wind speeds and high cloud cover that leads to a prolonged (at least 24-hour) drop in the capacity utilization of photovoltaics and wind farms below 20%. This necessitates maintaining dispatchable capacity in the system to ensure the continuity of electricity supply.
- The dark doldrums of 4–14 November 2024 illustrate the significant gap that must be filled by dispatchable sources, whose costs are not accounted for in LCOE calculations for non-dispatchable sources. In Germany, the average share of non-dispatchable sources during this period dropped from an annual average of 43% in 2024 to just under 15%.

- **There are numerous alternatives to LCOE that account for the full cost each technology imposes on the power system in different ways**. However, not all of them are easily implementable due to the complexity of calculations and the extensive data required. **Indices such as VALCOE and LCOLC, while relatively simple in structure, offer a more comprehensive representation of the actual costs of different electricity sources for the entire system**.

- For gas-fired generation, VALCOE decreases after accounting for its advantages as a dispatchable source, while for nuclear power, it remains unchanged. In contrast, for non-dispatchable sources, VALCOE is higher than LCOE.

- **Given the incomplete picture of system-wide costs associated with using LCOE to assess individual energy sources, we recommend supplementing the LCOE calculations published in Poland and the EU with at least one of the simpler alternative indices**. A suitable choice would be the **VALCOE or LCOLC metric**.

What is LCOE? Advantages and Disadvantages of a Popular Metric

The levelized cost of electricity (LCOE) is one of the most widely used indices for evaluating the profitability of investments in electricity generation sources.

Various institutions use LCOE as a measure of the cost-effectiveness of different technologies, including the International Energy Agency (IEA, 2024a), the Joint Research Centre of the European Commission (JRC) (Huld, Jaeger-Waldau, Szabo, 2014), the International Renewable Energy Agency (IRENA, 2024), and public institutions in many countries, including Poland.[1] The calculation of LCOE is based on two key concepts: net present value (NPV), which estimates the project's value, and total life cycle (TLC), which defines the project's total duration:

$$TLC = \sum_{t=1}^{T} \frac{C_t}{(1-r)^t} = \sum_{t=1}^{T} \frac{I_t+M_t+F_t}{(1-r)^t},$$

where:

C – total annual cost,

I_t – annual capital expenditure in year *t*,

M_t – maintenance cost in year *t*,

F_t – fuel and variable costs in year *t*,

r – discount rate,

t – analysis period,

T – project life cycle in years (IEA, 2020).

[1] LCOE is used in calculations by institutions such as the National Centre for Research and Development (NCBiR) (www1).

TLC is then normalised based on electricity production over the entire operational period to eliminate scale effects, resulting in the final LCOE value:

$$LCOE = \frac{\sum_{t=1}^{T} \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^{T} \frac{E_t}{(1+r)^t}},$$

where:

E_t – electricity production in year t (IEA, 2020).

As can be observed, **the basic version of LCOE takes into account only two types of factors**. The first is **the costs associated with the construction and operation of the electricity generation process for a given facility**, and the second is **the total annual electricity production**.

While this approach may be more acceptable for goods that can be easily stored and are independent of infrastructure, for electricity, it represents **a significant oversimplification. The role of the electricity market is not just to produce as much energy as possible at the lowest cost over the course of a year. What is crucial—unlike in many other industries—is the ability to generate and deliver the exact amount of electricity required by all consumers at any given moment**. This is reflected in electricity bills, where the charge for consumed energy typically accounts for only about half of the total costs. The other half consists of system maintenance expenses, such as distribution fees and capacity charges. However, **LCOE does not account for system costs, which limits its applicability as a metric for assessing the optimal structure of the national energy mix**.

The reliance on the concept of LCOE stems, among other factors, from its long-standing history as a metric, having been in use since the second half of the 20th century. The simplifications inherent in LCOE were acceptable at a time when energy systems primarily depended on fossil fuel combustion and nuclear power plants, given their similar stability within the grid (IEA, 2020). However, the fuel and energy crises of 1973–1980 led to a sharp rise in fossil fuel prices. In just the first three months following the introduction of the OPEC embargo in October 1973, the nominal price of oil in the United States surged by 135% (for comparison, following Russia's invasion of Ukraine, oil prices rose by 20% within three months) (Śliwowski, 2022). The 1970s also saw the rise of climate and environmental movements (Thomson, 2016), as well as an increasing number of warnings from the scientific community regarding the impact of CO_2 emissions on climate change. In 1977, Frank Press, the Chief Scientific Adviser to the White House, issued an official memorandum to President Carter on this issue (www2). Both of these factors contributed to a gradual transition away from fossil fuels and the expansion of low-emission energy sources, including photovoltaics and wind power.

A key feature of LCOE is its focus on achieving investment returns and limiting the risk exposure of investors and the financial sector. LCOE is a far better index for an investment fund than for a market regulator

or a transmission system operator. Interestingly, the use of discounted costs for evaluating profitability in the energy sector has a history just as turbulent and crisis-driven as the application of LCOE itself.

The rapid rise in the use of discounted cash flows (DCF) to assess project value in the British coal mining industry occurred at the turn of the 18th and 19th centuries (Brackenborough, McLean, Oldroyd, 2001), although the concept, widely popularized in the 16th century, was already known to the mining sector at least since the early 18th century. The popularity of discounted cash flows was linked to rising investment costs associated with extracting coal from increasingly deeper deposits (CAPEX), along with growing pressure from the financial sector to optimize capital utilization amid the political and economic instability caused by the French Revolution and the Napoleonic Wars.

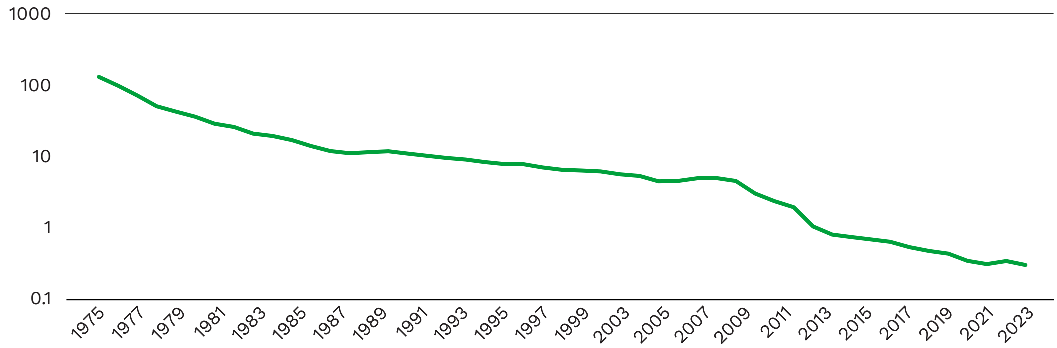
Similarly, in the case of LCOE, **its growing popularity was largely driven by inflation and increasing pressure to develop capital-intensive (high-CAPEX) nuclear and renewable energy sources, prompted by the oil crisis of the 1970s** (Farrar, Woodroff, 1973).

By the early 1990s, the limitations of LCOE as the primary evaluation metric had begun to be recognized, as power grids had become more complex and diversified compared to 20 years earlier. One of the first proposed alternatives was the "System Value" (SV) indicator. Instead of reflecting the cost of electricity generation by individual units in the system, it focused on the overall change in costs for the entire power system when a specific technology was used, taking into account electricity generation costs, the costs of alternative technologies, and optimal system integration (IEA, 2020). However, this indicator proved to be significantly more complex to calculate for investment purposes than LCOE. **The primary advantage of LCOE over alternative metrics—its simplicity—combined with the still relatively low share of non-dispatchable renewable energy sources in the 1990s and early 21st century, resulted in a lack of interest in adopting alternative solutions** (IEA, 2020).

Non-Dispatchable Sources – A Major Oversight in LCOE?

A more than 300-fold decline in photovoltaic panel prices between 1970 and 2023 – from over USD 100/W in the mid-1970s to USD 6/W in 2000 and USD 0.3/W in 2023 – along with the steady reduction in wind farm construction costs, has **resulted in a significant increase in the share of these sources in electricity generation**.

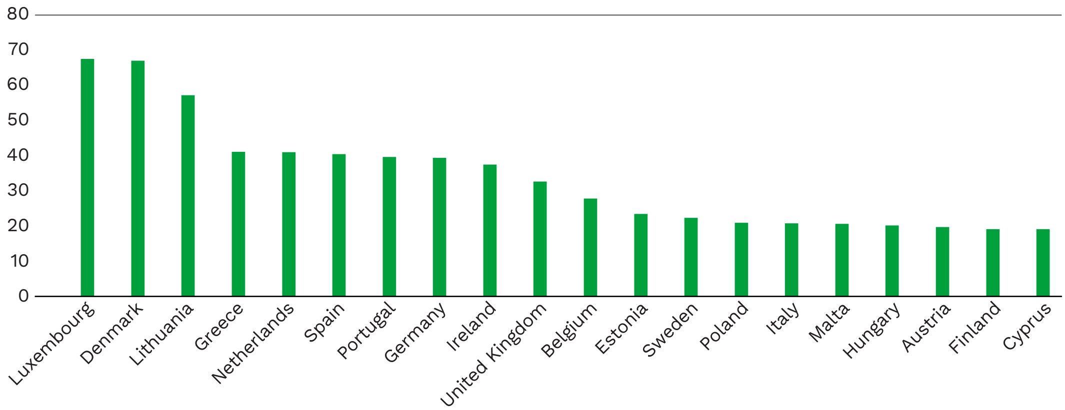
Figure 1. Market price of photovoltaic panels per 1W (in USD, inflation-adjusted prices, logarithmic scale)



Source: prepared by PEI based on (www3).

According to data from the International Atomic Energy Agency, in 2023, non-dispatchable sources accounted for over 13% of global electricity production, and by 2028, this share is expected to nearly double—to nearly 25% (www4). In the EU, however, the share of non-dispatchable sources is significantly higher. In 2023, wind farms and photovoltaics together generated 27% of the EU's electricity, with some countries exceeding 40% (www5).

Figure 2. Share of major non-dispatchable sources (photovoltaics and offshore / onshore wind farms) in electricity production in selected EU countries and UK (%)



Source: prepared by PEI based on Ember Climate data.

At the same time, wind turbines and photovoltaics either cannot provide ancillary services or can only do so in a limited capacity. They are the only energy sources that lack the capability for a so-called black start (i.e., restoring generators or power system components after blackouts (IEA, 2020).

Wind power plants have relatively low inertia,[2] while photovoltaics have none. While this is not necessarily a disadvantage—as seen in the case of pumped-storage power plants—it becomes problematic for non-dispatchable sources. In such cases, sudden fluctuations in electricity generation can occur, leaving the transmission system operator with little time to react by adjusting output from other sources to balance the system.

Table 1. Availability of ancillary services by power technology

Technology	Inertia	Frequency			Voltage		System Restart	Reserve Capacity		
		Primary Response	Secondary Response	Tertiary Response	System Strength	Reactive Power	*Black start*	Regulating Reserve	Contingency Reserve	Load Following Reserve
Nuclear	○	-	-	×	○	○	○	-	×	×
Bio	○	○	○	○	○	○	○	○	○	○
OCTG	○	○	○	▲	○	○	○	▲	○	▲
CCTG	○	○	○	○	○	○	○	○	○	○
Coal-CCS	○	○	○	○	○	○	○	○	○	○
CCGT-CCS	○	○	○	○	○	○	○	○	○	○
BECCS	○	○	○	○	-	○	○	○	○	○
Wind turbine	○	×	×	×	-	○	-	×	×	×
Solar	-	×	×	×	-	○	-	×	×	×
Pumped Hydro Storage	○	▲	▲	▲	○	○	▲	▲	▲	▲
Battery	-	▲	▲	▲	-	○	▲	▲	▲	▲

Note: The technology can be used by the power plant: ○ to provide the service, ▲ to provide the service, but might be limited by the energy availability and economic and environmental factors, × the technology can technically provide the service, but its efficiency is significantly limited for economic reasons (e.g., nuclear power plants, wind farms, and photovoltaic plants become less profitable if they do not operate at their maximum possible capacity at a given time).

Source: prepared by PEI based on IEA (2020).

These characteristics of non-dispatchable energy sources necessitate balancing them with dispatchable capacity. Currently, this is primarily achieved through gas-fired power plants and, to a lesser extent, coal-fired and pumped storage power plants. In the future, battery-based energy storage systems and gas-fired power plants using biomethane and hydrogen from zero- and low-carbon sources are expected to play a greater role.

[2] An electrical system with high inertia is slower to adjust its parameters, meaning it cannot rapidly increase or decrease electricity generation (Strupczewski, 2014).

However, **this cost is usually not included in LCOE calculations** (although some institutions publish LCOE+ with the added cost of energy storage) (Lazzard, 2024). Even accounted for (e.g., when calculating non-dispatchable sources together with battery capacity), these calculations typically consider only daily and seasonal fluctuations. **They do not, however, take into account extreme conditions that are highly unfavourable for non-dispatchable generation, such as the so-called "dark doldrums" (*Dunkelflaute*), which national power systems must be prepared for**.

Some EU countries (including Poland) regularly experience dark doldrums (ACER defines a dark doldrum as a situation in which the capacity factor of PV and wind farms falls below 20% for more than 24 hours) (www6). According to calculations by Dutch researchers (Li et al., 2021), in the 32 years they analysed (1985–2016), there was not a single year in which this phenomenon did not occur in Germany, Norway, and the UK. Additionally, in most of the analysed years, it was also observed in the other eight Northern European countries studied, including Poland.

The dark doldrum event of 4–14 November 2024 illustrates the scale of the gap that must be covered by dispatchable sources, the cost of which is not included in the LCOE of non-dispatchable sources. **In Germany, the average share of non-dispatchable sources during this period fell from an annual average of 43% in 2024 to just under 15%**. At the same time, the German economy had to import 1.9 TWh of electricity—12% of Germany's total electricity demand during this period—to meet its energy needs.

Germany's average residual power demand in 2024 was 32 GW, rising to 53 GW during the most recent dark doldrum. Battery storage, despite its rapidly decreasing costs, stores energy for only four hours of operation. In the case of a multi-day generation gap, the cost of building a sufficient number of storage facilities would amount to hundreds of billions of dollars. This shortfall had to be compensated for by gas- and coal-fired electricity (Juszczak, 2024).

Relying solely on LCOE is becoming increasingly problematic not only in the EU. In **Texas, in December 2022, the average capacity factor of wind farms was 32%. However, the variability in the capacity utilization of Texas wind power plants was significant, ranging from 5% to 70%**. This wide fluctuation in capacity utilization necessitates maintaining greater dispatchable capacity. **According to calculations by J.P. Morgan analysts, on 23 December 2022—during a period of high energy demand and low generation from non-dispatchable sources—even a fivefold increase in the installed capacity of photovoltaics and wind farms would reduce the need for gas-fired dispatchable capacity by only 20%** (JP Morgan, 2023).

Currently, several alternatives to LCOE exist in the scientific literature and reports from international institutions. These indices vary in complexity—both in terms of calculations and the data required. Some remain purely theoretical, while others, such as the Value-Adjusted Levelized Cost of Electricity (VALCOE), developed by the International Energy Agency in 2018 (IEA, 2018), have gained broader recognition and are published alongside LCOE calculations.

In Poland, the public debate currently relies primarily on LCOE. However, given the increasing share of renewable energy sources in the system, we believe this approach may distort the total costs of different options for the future electricity mix. For this reason, we present some of the available alternatives.

Selected Alternative Metrics to LCOE

Value-Adjusted Levelized Cost of Electricity (VALCOE)

VALCOE was developed by the International Energy Agency in 2018 (IEA, 2018). Its calculation begins with the average LCOE of various projects using the technology under analysis. Based on the results of the hourly Global Energy and Climate Model (GEC) developed by the IEA, it incorporates additional components—energy value (comparing individual units to the system average), capacity, and flexibility[3]—into the final result. For each technology, the estimated values are compared to the system average and applied as adjustments to the LCOE (IEA, 2024b).

Table 2. Comparison of projected LCOE and VALCOE values in the 'Stated Policies Scenario' for 2050 across selected world regions (USD/MWh)

Source	USA		EU		China	
	LCOE	VALCOE	LCOE	VALCOE	LCOE	VALCOE
Nuclear Power Plants	100	100	110	110	65	65
Open Cycle Gas Turbine (CCTG)	120	75	N/A	N/A	140	90
Photovoltaics	25	60	35	90	25	70
Onshore Wind	30	40	55	60	35	50
Offshore Wind	50	60	35	40	40	40

Source: prepared by PEI based on IEA (2023).

The LCOE adjustment proposed by the IEA, which is used to calculate VALCOE, significantly influences the assessment of the cost-effectiveness of individual electricity generation technologies. The VALCOE for gas combustion decreases when its advantages as a dispatchable source are considered, while for nuclear power, it remains constant. In contrast, for non-dispatchable sources, VALCOE is higher than LCOE.

[3] The exact methodology for calculating VALCOE, including formulas, can be found in the IEA document (p. 54), along with the formulas for calculating each component of the LCOE adjustment (IEA, 2024b, p. 55).

The greatest impact of VALCOE is observed in photovoltaics, where the cost of generating 1 MWh increases by more than twofold compared to LCOE after adjustments. Conversely, the smallest differences are seen in offshore wind farms, which appear to be 'the most stable among the uncontrollable.' VALCOE—by the IEA's own admission—does not account for the full costs of grid integration or environmental costs. It is a modification of LCOE rather than a completely new metric developed from scratch. The cost variation resulting from using VALCOE instead of LCOE remains one of the smoothest among the alternative indices.

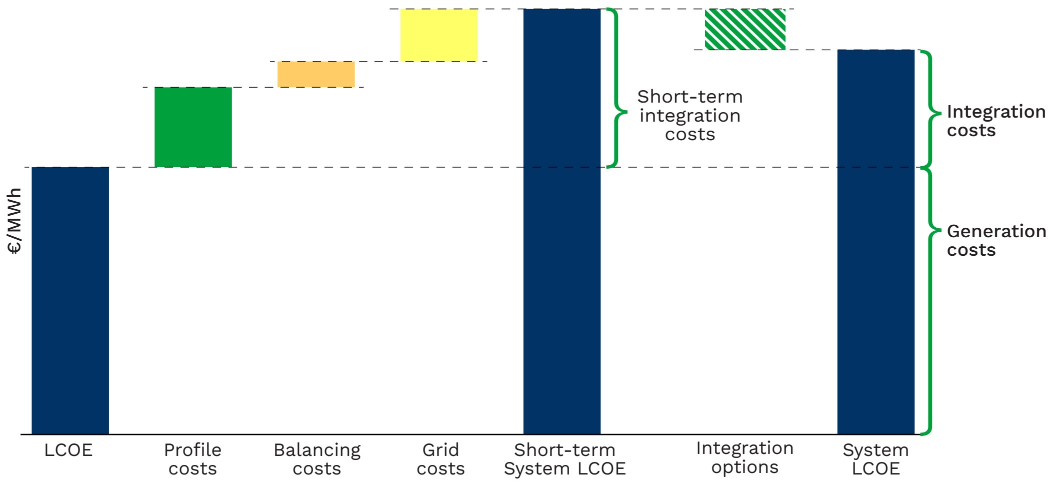
Other useful metrics proposed by the IEA include the **Levelized Cost of Storage** (LCoS), which is calculated analogously to LCOE and represents the discounted cost of storing energy—primarily through batteries. Another metric is the **Levelized Avoided Cost of Electricity** (LACE), originally developed and promoted by the U.S. Energy Agency, which reflects the costs that would be incurred to deliver electricity if a project were replaced by an alternative. While these metrics still do not provide a complete picture of the electricity system or the need to maintain available capacity in case of extremely adverse weather conditions, such as a dark doldrum, their use helps bring valuation closer to other, more complex metrics that account for the costs of operating the electricity system.

System LCOE

Developed by Hirth et al. (2013), the System LCOE (sLCOE) indicator is based on the concept of **'marginal integration costs,'** which include, among other factors, the costs of electricity overproduction, backup generating capacity, balancing, network infrastructure, and the reduction of full-load hours. These costs are added to the marginal cost of electricity generation.In later publications (Hirth, Ueckerdt, Edenhofer, 2015), the method was refined and defined as the difference between the market value of energy from a non-dispatchable source (e.g., wind) and the average system load-weighted electricity price.[4]

[4] The average electricity price serves as the benchmark for estimating integration costs. It corresponds to the market value of a reference technology that generates electricity in perfect correlation with demand.

Diagram 1. Components of the sLCOE indicator



Source: prepared by PEI based on Ueckerdt et al. (2013).

The results of the model used to calculate the System LCOE for wind farms indicate a significant increase in grid integration costs as the share of wind power in the energy mix rises. When these sources have a low share in the system, their integration cost remains minimal. However, when non-wind sources constitute 30–40% of the electricity generation mix, integration costs add an additional 35–50% to the cost of electricity production alone. The largest component of integration costs is the so-called profile costs.[5] This leads to an important conclusion: increasing marginal integration costs may become an economic barrier to the further development of non-dispatchable renewable energy sources, even if generation costs continue to decline. However, the authors point out that, in the long term, adjustments to generation capacity can significantly reduce integration costs. Therefore, a well-designed grid based on non-dispatchable sources does not necessarily result in high costs for the electricity system in the long run.

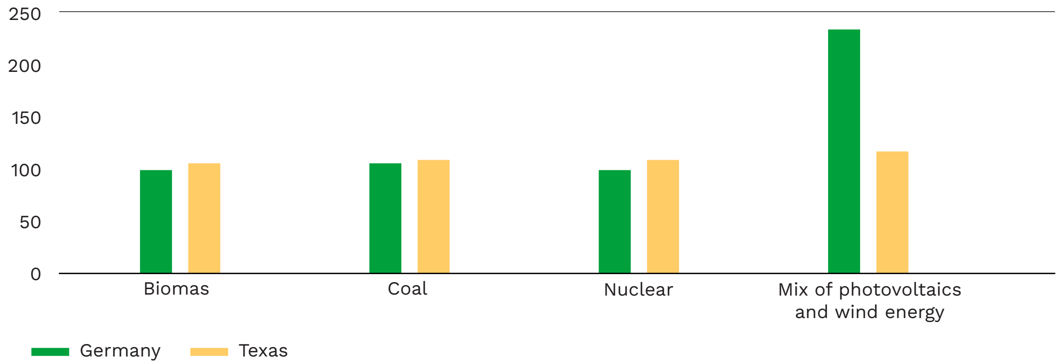
Levelized Full System Costs of Electricity

One of the latest alternatives to LCOE is the **Levelized Full System Costs of Electricity (LFSCOE)**, proposed by Robert Idel (2022). It is based on the premise of calculating the full cost an energy source would incur if the system relied entirely on it and energy storage. LFSCOE uses annual data on

[5] These costs arise from the uncontrollability of wind power, leading to high variability in energy production. Profile costs consist of three components: the costs of overproduction, backup generation capacity, and the reduction of full-load hours in conventional power plants.

hourly capacity utilization and demand co-factors (from Germany and Texas) to determine the optimal combination of generation and storage. It then calculates the average cost per 1 MWh, discounted over the lifetime of the generation asset, similar to LCOE. The development of this index also led to the creation of LFSCOE-95, an updated version that assumes only 95% of total demand must be met by a specific electricity source and energy storage. This approach is more aligned with reality, as it allows for moderate dispatchable capacity to remain in the system. Even with this assumption, a system based on 95% non-dispatchable sources remains more expensive than a biomass- or nuclear-based alternative.

Figure 3. LFSCOE-95 of selected energy sources for Germany and Texas (USD/MWh)



Source: prepared by PEI based on Idel (2023).

Levelized Cost of Load Coverage

The **Levelized Cost of Load Coverage (LCOLC) index**, proposed by researchers at Friedrich-Alexander University in Erlangen-Nuremberg and the Technical University of Nuremberg, is based on the demand that must be met to fulfill the projected needs of a given electricity system. For the various available technological solutions, the available power plant capacities (X_{LCOLC}) and generation volumes from different sources (Q_{LCOLC}) are determined at minimum cost to ensure the specified demand profile is met exactly. Optimal generation capacities and output levels are thus determined by solving the problem of minimizing the cost of meeting the assumed electricity demand. LCOLC is then calculated based on the minimum capacity costs and production quantities according to the following formula:

$$LCOLC = \frac{Net\ present\ value\ of\ annual\ costs\ (X_{LCOLC}, Q_{LCOLC})}{Annual\ electricity\ generation\ (Q_{LCOLC})}.$$

The results of the model developed by researchers indicate that even with a significant decrease in battery storage costs, **the LCOLC for non-dispatchable technologies remains significantly higher than the LCOE (Grimm, Oechsle, Zöttl, 2024)**. In a variable demand scenario, although the LCOEs of wind power and photovoltaics are significantly below EUR 50/MWh, adding balancing costs for a mix of wind farms and photovoltaic panels increases the LCOLC. It ranges from EUR 70.8/MWh (when balanced with a combination of battery storage, natural gas, and hydrogen) to as much as EUR 210.7/MWh (when relying solely on battery storage).

Like all other indices, LCOLC requires a more complex calculation than LCOE. The results also depend on the electricity demand forecasts used in the model. However, optimization models are not new in energy analysis, as exemplified by the PEI Energy Mix model (Juszczak et al., 2023; Miniszewski, Pilszyk, 2023). With appropriate adaptation, some of these models, in addition to scenario analysis for full decarbonization, could also be used to determine the LCOLC index or its modifications.

Table 3. LCOE vs. LCOLC for different technologies (EUR/MWh)

Technology, Support technology	LCOE	LCOLC			
		Battery storages + gas	Battery storages	Battery storages, gas, hydrogen	Battery storages, hydrogen
Wind Power	40.69	90.61	x	x	x
Photovoltaics	20.59	100.35	x	x	x
Photovoltaics and Wind Power	x	80.11	210.7	70.8	70.85

Source: prepared by PEI based on Grimm, Oechsle, and Zöttl (2024).

Summary

Despite the prevailing consensus in the scientific literature on the incompleteness of LCOE and the numerous issues arising from its use in assessing the feasibility of a technology, it remains the most commonly used metric for this purpose. The simplicity of its calculation methodology and the limited data required play a decisive role in its widespread adoption. Additionally, the fact that it is the preferred metric of the financial system—due to its focus on investor-controlled costs—is not insignificant.

The increasing share of non-dispatchable sources in European electricity systems leads to additional costs, which rise as their proportion in the energy mix grows. These costs become particularly evident during energy price spikes in periods of so-called dark doldrums—a combination of low wind speeds and high cloud cover. Such conditions cause a multi-day reduction in the energy production capacity of variable renewable sources, such as photovoltaics and wind power, and necessitate greater reliance on dispatchable sources—primarily natural gas and coal—resulting in significantly higher CO_2 emissions during these periods.

Failing to account for additional costs associated with maintaining available dispatchable power source capacity in the system, higher grid costs, or costs resulting from an oversupply of electricity in the metrics used for formulating and evaluating Polish and EU strategic documents may lead to inaccurate assessments of the total costs of individual investments in national electricity systems. Consequently, this could result in suboptimal and irresponsible electricity mix planning.

Comprehensive metrics, however, are often too complex and require excessive amounts of hard-to-access data, making them difficult to introduce into widespread use. Therefore, **we recommend supplementing the published Polish and EU LCOE calculations with at least one simple alternative**. A good choice could be the **VALCOE index**, used by the International Energy Agency. Although it does not fully account for all the components mentioned above, it still provides a more comprehensive representation of the true costs incurred by national electricity systems than LCOE. Another interesting option is **the LCOLC index**, proposed by researchers at Friedrich-Alexander University Erlangen-Nuremberg and the Technical University of Nuremberg, which enables the model—and therefore the cost assessment—to be adjusted to specific demand and available or forecasted capacity in the system.

We acknowledge that this working paper does not provide a comprehensive comparative analysis of all metrics available in the literature. Our primary aim is to highlight the shortcomings of LCOE, which are rarely addressed in Polish public debate, and to draw attention to the existence of more effective alternatives. We hope that the discussion on supplementing or refining LCOE and other energy cost indices for Polish and international strategic documents—already a necessity today—will serve as an important step towards the responsible, efficient, and sustainable transformation of the Polish energy sector in the future.

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